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الشكر والتقدير

بِسۡمِ ٱللَّهِ ٱلرَّحۡمَٰنِ ٱلرَّحِيمِ

﴿وَمَا تَوْفِيقِي إِلَّا بِاللَّهِ، عَلَيْهِ تَوَكَّلْتُ وَإِلَيْهِ أُنِيبُ﴾

– سورة هود، الآية 88

والصلاة والسلام على سيدنا محمد، خاتم الأنبياء والمرسلين، وعلى آله وصحبه أجمعين.

أما بعد، فبحمد الله وتوفيقه، وبتيسيره وحده، تمكّنا من إتمام هذا العمل، سائلين المولى عز وجل أن يجعله خالصًا لوجهه الكريم، نافعًا لنا ولغيرنا، ومثمرًا في ميدانه.

وإقرارًا بفضل العطاء، وردًّا للجميل، نتقدّم بأسمى عبارات الشكر والتقدير إلى الأستاذ الفاضل سرهود هشام، الذي لم يدّخر جهدًا في تقديم النصح والإرشاد، وكانت توجيهاته نورًا أضاء لنا طريق الإنجاز. نسأل الله أن يجزيه عنّا خير الجزاء، وأن يبارك له في علمه وعمله، ويجعله منارةً تُضيء دروب طلبة العلم والمعرفة.

كما نتوجّه بخالص الامتنان والتقدير إلى الأستاذة مراح هناء، وإلى الزميل العزيز فاضل معمر، على ما قدّماه من دعم ومساندة تركت أثرًا بالغًا في إنجاح هذا العمل.

ولا يسعنا في الختام إلا أن نعبّر عن عميق امتناننا لأساتذتنا الكرام، الذين كان لهم الفضل في تكويننا وتأطيرنا طيلة مسيرتنا الجامعية. كما نخصّ بالذكر زملاءنا من دفعة 2025، وكل من أسهم في هذا العمل بفكره وجهده ودعمه، فلكم منّا أسمى عبارات الشكر والعرفان، ودعواتٌ صادقة أن يجزيكم الله خير الجزاء، ويوفّقكم ويسدّد خُطاكم في دروب العلم والمعرفة.

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إلى العزيز الذي حملت اسمه فخرًا، إلى من كلّله الله بالهيبة والوقار،

إلى من حصد الأشواك عن دربي وزرع لي الراحة بدلاً منها،

إلى أبي...

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إلى من علّمتني الأخلاق قبل أن أتعلمها، إلى الجسر الصاعد بي إلى الجنة،

إلى اليد الخفية التي أزالت عن طريقي العقبات، ومن ظلت دعواتها تحمل اسمي ليلًا ونهارًا...

أمي، محبوبتي وملهمتي.

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إلى من رافقني بالقلب قبل الدرب،

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وبين طيات الطريق تنفست سلامًا وفرحًا وامتنانً

CHAIB
Ouiem

الاهداء

أهدي هذا العمل المتواضع إلى من غرست في قلبي القيم، وأنارت دربي بحبها ودعواتها، إلى من كانت ولا تزال الحضن الدافئ، والسند الثابت...

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إلى كل من أحببتهم وأحبوني، وإن خانتني الذاكرة في تعداد أسمائهم، فمكانهم في القلب لا يُنسى.

إلى كل من كان عوناً لي، بكلمة، بدعاء، بابتسامة، أو لحظة دعم.

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HAMMADI
Manel

Abstract:

This study presents the simulation and analysis of a Grid-Connected photovoltaic system. The model provides a detailed representation of key components, including the solar array, boost converter, and Grid-Connected inverter. An optimized DC/DC converter control strategy has been implemented to maximize energy extraction, ensuring efficient Maximum Power Point Tracking (MPPT). The Grid-Connected inverter facilitates seamless energy transfer by maintaining a stable DC-link voltage. Modeling and control strategies are developed and validated using MATLAB/Simulink, with simulation results demonstrating the system’s control performance and dynamic behavior under varying conditions.

Keywords: Photovoltaic, Boost Converter, Inverter, Grid, MPPT, Perturb and Observe (P&O), MATLAB/Simulink.

الملخص:

تتناول هذه الدراسة محاكاة وتحليل نظام كهروضوئي متصل بالشبكة الكهربائية. يقدّم النموذج تمثيلًا تفصيليًا للمكونات الأساسية، بما في ذلك المصفوفة الشمسية، المحول المعزز (Boost Converter)، والعاكس المتصل بالشبكة .لضمان استخلاص الطاقة القصوى، تم تنفيذ استراتيجية تحكم محسّنة للمحول DC/DC، مما يحقق كفاءة عالية في تقنية تتبع نقطة الطاقة القصوى. (MPPT) يعمل العاكس المتصل بالشبكة على نقل الطاقة المستخلصة من الوحدة الكهروضوئية إلى الشبكة الكهربائية مع الحفاظ على جهد التيار المستمر (DC-link voltage) مستقرًا .تم تطوير استراتيجيات النمذجة والتحكم والتحقق من صحتها باستخدام MATLAB/Simulink، حيث تُظهر نتائج المحاكاة أداء النظام واستجابته الديناميكية تحت ظروف تشغيل مختلفة.

الكلمات المفتاحية :الطاقة الكهروضوئية، المحول المعزز، العاكس، الشبكة، تقنية MPPT، طريقة الإزعاج والمراقبة (P&O)،MATLAB/Simulink

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VSI : Voltage - Source Inverter.

PV : Photovoltaic.

DC / DC: converter

PWM: Pulse Width Modulation.

MPPT: Maximum power point tracking.

PLL: Phase Locked Loop.

AC: Alternating Current.

DC: Direct Current.

DC /AC: Inverter

P&O: Perturb and Observe

General Introduction

General Introduction

In recent years, solar-based power generation—particularly photovoltaic (PV) systems—has gained significant traction as part of the global transition toward sustainable and environmentally friendly energy sources. According to the International Energy Agency (IEA), global PV installations reached approximately 98 GW in 2017, marking a 29% increase from the previous year, with China accounting for 32% of the total installed capacity.

Grid-connected PV systems represent one of the most widely adopted solar energy applications. Their effective operation relies on seamless integration between the PV generator, control mechanisms, and power electronics. A crucial component of this integration is precise current control within the inverter that links the PV system to the grid. Additionally, Maximum Power Point Tracking (MPPT) techniques are employed to optimize power extraction from the PV source, while DC-DC boost converters regulate voltage levels and enhance energy conversion efficiency.

Motivation

The significance of this research lies in addressing a fundamental aspect of renewable energy systems: current control in Three-Phase Grid-Connected photovoltaic systems. Precise current regulation improves power quality, ensures synchronization with the grid, and enhances overall system stability and reliability. Given the dynamic nature of solar irradiance and temperature fluctuations, robust and adaptive control strategies are essential for optimizing performance.

This study aims to analyze and simulate current control strategies for grid- connected PV systems, focusing particularly on advanced techniques such as Model Predictive Control (MPC). The objective is to enhance system efficiency, dynamic response, and overall energy utilization under variable environmental conditions.

Thesis Structure

This research is structured into three core chapters:

- **Chapter One:** provides a comprehensive overview of PV systems, detailing the photovoltaic effect, cell types, electrical characteristics, modeling approaches, and essential system components. Additionally, it outlines PV system classifications.
- **Chapter Two:** explores Maximum Power Point Tracking (MPPT) methods, presenting

- the simulation of the PV system and the implementation of the Perturb and Observe
- (P&O) algorithm via a DC-DC boost converter to maximize power extraction.
- **Chapter Three:** examines current control in Three-Phase Grid-Connected PV systems, covering converter types, inverter configurations, and system modeling. Furthermore, it discusses advanced control techniques, including Voltage Source Inverter (VSI) control, Phase-Locked Loop (PLL) synchronization, and a proposed Model Predictive Control strategy for enhanced system performance

CHAPITER I

PHOTOVOLTAIC SYSTEMS

Introduction

As the world continues to grapple with the depletion of fossil fuels and the environmental damage caused by their exploitation, the need for sustainable and renewable sources of energy has become increasingly urgent. Among the various alternatives, solar energy stands out as a clean, abundant, and inexhaustible resource. Photovoltaic (PV) technology, which directly converts sunlight into electricity, has emerged as a viable and promising solution to meet the growing global energy demand.

Every day, the sun generously supplies the Earth with abundant energy. This immense resource can be effectively harnessed through the utilization of photovoltaics, a technology that converts solar energy into electricity. Photovoltaic (PV) technology, also known as solar electric, is recognized as one of the most innovative and swiftly expanding renewable energy resources employed for electricity generation on a global scale. The adoption of PV technology offers a multitude of advantages, including its enduring nature, universal availability, eco-friendliness, affordability, absence of pollution, and minimal maintenance requirements [1].

The applications of photovoltaic systems encompass a wide range of energy services, catering to both remote areas and network utilities. These applications include providing lighting to villages, powering solar home systems, illuminating streets and camps, facilitating traffic management, supporting medical facilities in remote regions, enabling telecommunication stations, facilitating battery charging, and operating water pumping and purification systems. The utilization of photovoltaic systems for electricity production originated in the 1970s and has since experienced substantial global growth, despite initial high capital costs [2].

1. General Knowledge

1.1 History

Photovoltaic systems have been in use for 45 years. Their applications began with the space program for satellite radio transmission. They continued with maritime beacons and the equipment of remote sites worldwide, utilizing batteries to store electrical energy during sunless hours.

The key dates in the history of photovoltaic are listed below:

- 1839 The French physicist Edmond Becquerel discovered the process of using sunlight to generate electric current in a solid material. This is known as the photovoltaic effect.
- 1875 Werner Von Siemens presented his findings before the Berlin Academy of Sciences. An article on the photovoltaic effect in semiconductors was published, but until World War II, the phenomenon remained merely a laboratory curiosity.
- 1954 Three American researchers, Chapin, Pearson, and Prince, developed a high-efficiency photovoltaic cell at a time when the emerging space industry was seeking new solutions to power its satellites. They discovered that the photosensitivity of silicon could be enhanced by adding "impurities," a technique known as "doping," which is now used for all semiconductors.
- 1958 A solar cell with 9% efficiency was developed, and the first satellites powered by solar cells were launched into space.
- 1973 The first house powered by photovoltaic cells was built at the University of Delaware.
- 1983 The first solar-powered car traveled a distance of 4,000 km in Australia [3].

1.2 Solar Radiation

Solar radiation consists of photons with wavelengths ranging from ultraviolet (0.2 µm) to far-infrared (2.5 µm). The term Air Mass (AM) is used to characterize the solar spectrum in terms of emitted energy.

The total energy carried by solar radiation over the Sun-Earth distance is approximately 1350 W/m² (AM0) in space, outside the Earth's atmosphere (Figure 1). When solar radiation passes through the atmosphere, it undergoes attenuation and modification of its spectrum due to absorption and scattering by gases, water, and dust. For instance, the ozone layer absorbs part of the sunlight spectrum, particularly some of the ultraviolet rays, which are harmful to human health.

The direct solar radiation received at the Earth's surface (at a 90° inclination) reaches 1000 W/m² due to absorption in the atmosphere (AM1). This value changes depending on the inclination of the sunlight relative to the ground. The smaller the penetration angle θ, the greater

the thickness of the atmosphere that the rays must pass through, leading to a significant energy

loss. For example, the direct energy transported by solar radiation reaching the ground at an angle of 48° is approximately 833 W/m² (AM1.5) [4].

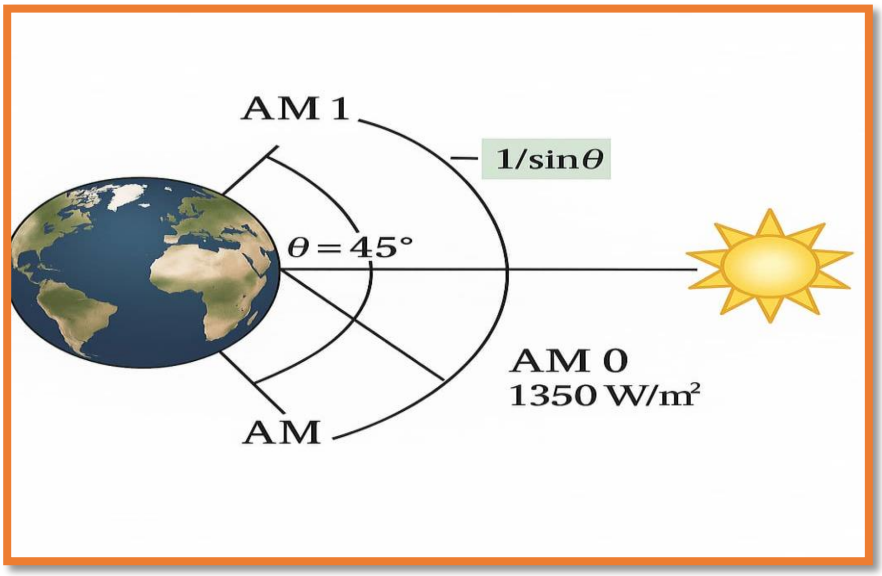


Figure (I.1): Standards for Measuring the Spectrum of Light Energy Emitted by the Sun, Concept of the AM Convention

At Ground Level, the Total Radiation Received by a Plane Surface with Any Inclination Consists of Three Main Components:

1.1.1Direct Radiation

This is the solar flux in the form of parallel rays coming from the solar disk without being scattered by the atmosphere [4].

1.1.2Diffuse Radiation

This is the portion of solar radiation that has undergone multiple reflections (scattering) in the atmosphere [4].

1.1.3Reflected Radiation

This is the part of solar illumination that is reflected by the ground. This radiation directly depends on the nature of the ground (e.g., clouds, sand.). It is characterized by a specific

coefficient related to the nature of the surface, called Albedo, which ranges from 0 to 1 ($0 \leq \varepsilon \leq 1$) [4].

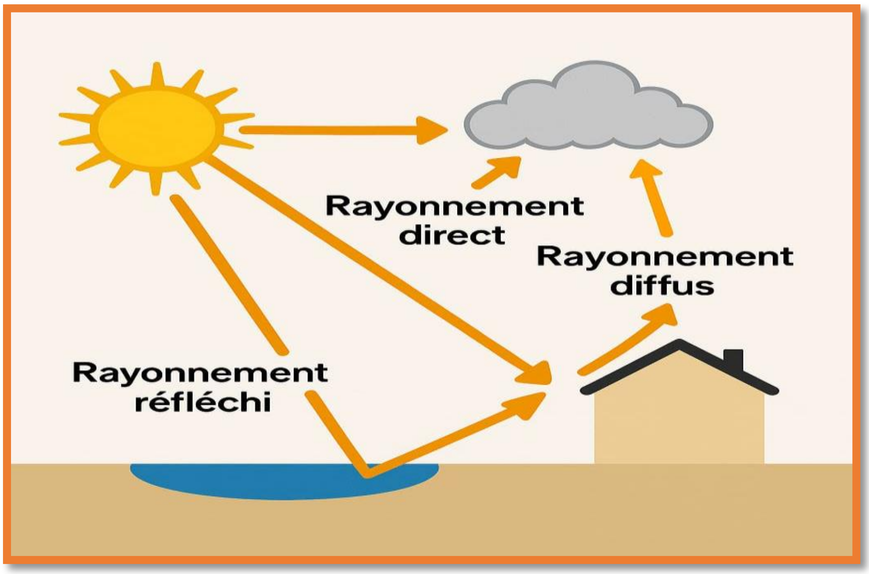


Figure (I.2): Different Components of Radiation [4].

1.1.4Global Radiation

A surface receives global radiation, which is the result of the combination of the three components: direct, diffuse, and reflected radiation [4].

1.3Solar Potential in Algeria

Algeria has one of the most significant solar resources in the world. The duration of sunshine across almost the entire national territory exceeds 2,000 hours annually and can even reach 3,900 hours, particularly in the High Plateaus and the Sahara.

The country possesses a substantial renewable energy potential, especially solar energy,

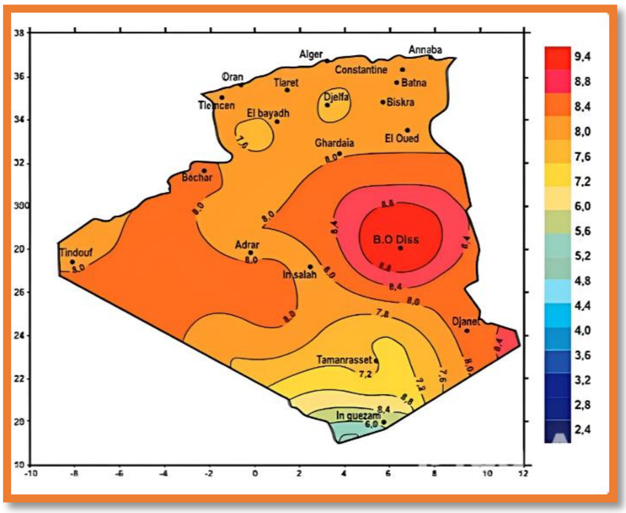


Figure (I.3): Daily Global Irradiation Received.

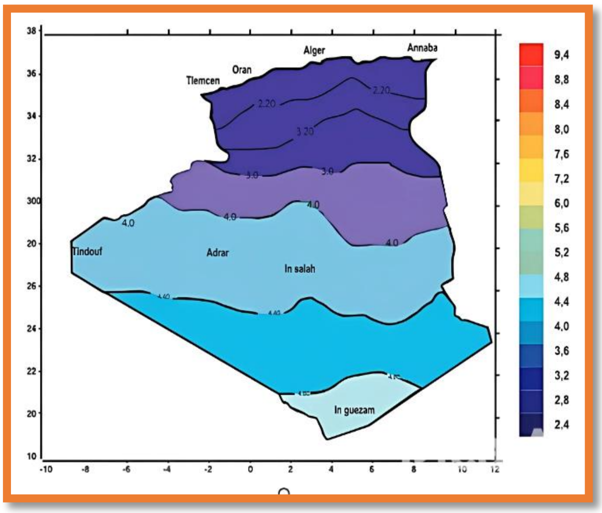
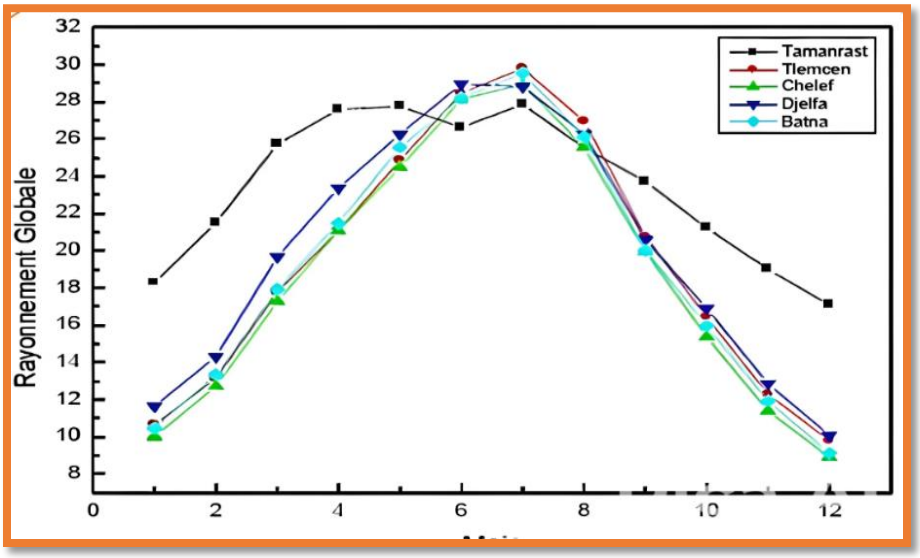


Figure (I.4): Daily Global Irradiation Received on a Horizontal Plane in December [6].



with solar radiation ranging from 3 kWh/m²/year in the north to 5.5 kWh/m²/year in the south, with sunshine duration between 2,000 and 4,000 hours per year [5].

A satellite assessment conducted by the German Space Agency revealed that Algeria has the highest solar potential in the entire Mediterranean basin, estimated at 169,440 TWh/year for solar thermal energy and 713.9 TWh/year for photovoltaics [6].

The maximum estimated value of global solar irradiation across the national territory is observed in June and July for various locations, as indicated in Figure (I.5) [7]. After this comparison, it is clear that the sites of Telemen and Delfi have the highest values, respectively [7].

2. Photovoltaic System

2.1 Photovoltaic energy

2.1.1 Definition

Figure (I.5): Highest Global Solar Radiation Values Across the National Territory [7].

Solar cell energy, s to the generation of electricity from s cells are made of semiconductor materials, typically silicon, which directly convert sunlight into electricity through the photovoltaic effect. Solar cell energy is considered a renewable and sustainable energy source that can be used to power various applications, ranging from small devices to large-scale solar power stations [8].

2.1.2The photovoltaic effect

Under the effect of solar radiation, the electron-hole pairs generated in the potential barrier are separated by the prevailing electric field. The holes (positive charge) are accelerated toward the P-doped region, while the electrons (negative charge) move toward the N-doped region. As a result, holes and electrons become the majority carriers on the outer surfaces of the P and N regions.

Thus, an electric voltage appears on both sides, and the device functions as an electrical generator. The current is collected through metallic contacts (electrodes). If these electrodes are connected to an external circuit, a direct current (DC) flow [9].

2.1.3 The principle of photovoltaic conversion

The photovoltaic cell comprises a semiconductor material that plays a crucial role in its functioning. When photons interact with a PV cell, they can either reflect off the cell, pass through it, or be absorbed by the semiconductor material. Only the absorbed photons provide the necessary energy to generate electricity. As the semiconductor material absorbs sunlight (solar energy), [illegible] erial. Through specific treatments applied to the material surface during manufacturing, the front surface of the cell is made more receptive to these dislodged electrons, allowing them to naturally migrate towards the surface of the cell [10].

By establishing a circulation of electrons in the external circuit, the photovoltaic cell operates as a generator. The voltage produced by the cell typically ranges between 0.3 V and 0.7 V,

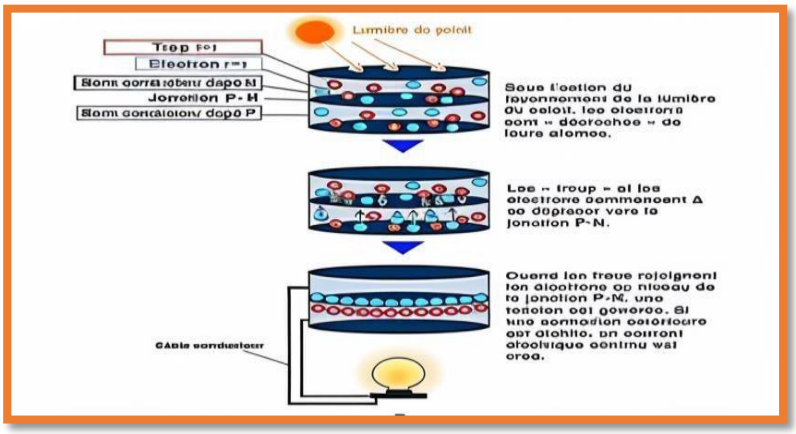


Figure (I.6) : Principe de la conversion photovoltaïque [9].

depending on factors such as the material used, its arrangement, and the temperature of the cell.

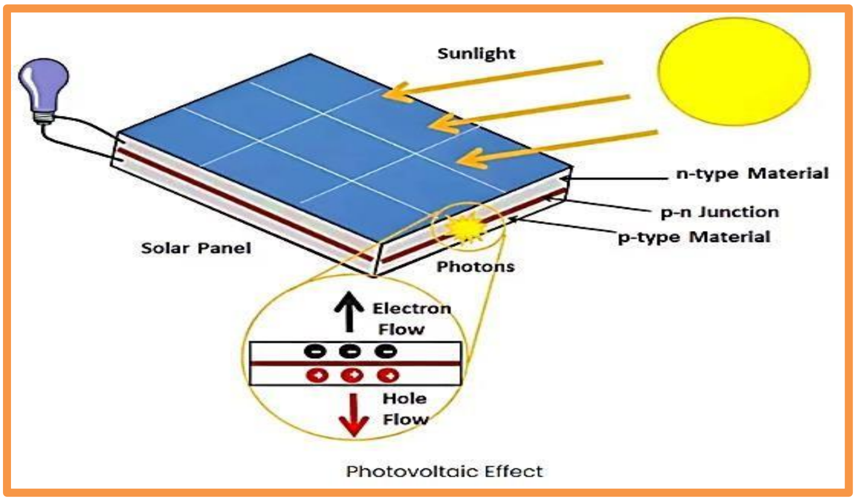
2.1.4 Type of photovoltaic cells

The cell is the most suitable conversion unit for the photovoltaic effect. The materials and the methodology used for the design of these cells influence the recovered energy. As a result, many solutions have been developed and they will be briefly introduced in next subsections [12].

- **Mon crystalli**

Figure (I.7): Photovoltaic cell structure.

Among the photov he monocrystalline are, in



general, those which have the best performances. Thus, the commercial solar cells obtained with this process can reach an efficiency of 15 to 18% [12].

- **Polycrystalline Silicon**

Polycrystalline silicon cells are cheaper than monocrystalline ones because the cell manufacturing processes are less stringent. However, their efficiency is lower. The manufacturing process is similar to the one previously described for silicon cell production but with less rigorous control. As a result, the cells obtained are less expensive but also less efficient (12.5% on average) [12].

- <u>**Amorphous silicon**</u>

The use of amorphous silicon for solar cells has demonstrated significant advantages in terms of both electrical properties and the manufacturing process. It offers a simple production process, low energy consumption, cost-effectiveness, and the ability to produce cells with large areas. However, despite the reduced production cost, amorphous silicon solar cells have two disadvantages. Firstly, they exhibit lower conversion efficiency compared to mono crystalline and polycrystalline silicon cells. Secondly, their performance decreases rapidly by 10% to 20% of their power during the first three to six months of operation [12].

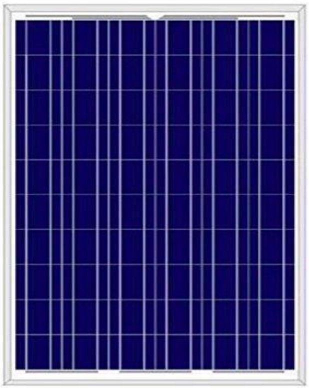
		
Single Crystal	**Polycrystalline**	**Thin film**

Table (I.1): Type of photovoltaic cells.

2.1.5 Electrical and Performance Characteristics of PV Cells

Understanding the electrical behavior of a photovoltaic (PV) cell is essential for analyzing and optimizing its performance. These characteristics are typically represented through the I-V (current-voltage) and P-V (power-voltage) curves, which define the electrical output under various operating conditions.

✓ **I-V and P-V Curves of a PV Cell**

Figure I. 9 shows I-V and P-V curves characteristic of the photovoltaic cell operating under standard test conditions.

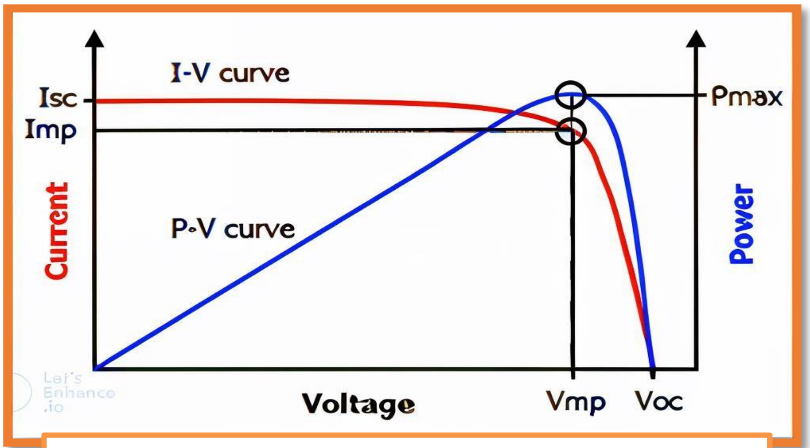


Figure (I. 8): I-V and P-V curves characteristic of the photovoltaic cell [13].

The I-V curve represents the relationship between the electrical current flowing through the PV cell and the voltage applied across its terminals, while the P-V curve demonstrates the relationship between electrical power output and the voltage across its terminals.

The I-V and P-V curves show five critical points, which are essential for understanding the operating characteristics of PV cell, which are:

- **Open Circuit Voltage (V_{OC}):** is the maximum possible voltage that PV cell can generate when the current through it is 0 amp, no load condition (open circuited).
- **Short Circuit Current (I_{SC}):** is the highest possible current that a cell can generate when the voltage across its terminals equals 0V (short- circuited" R=0").

- **Maximum Power Point (MPP):** is the point at where the PV cell operates at maximum power output (Pmax).
- **Current at Maximum Power Point (I_{mpp}):** represents the current produced by the PV cell when operating at the maximum power point. As shown in figure (I.8) its value is lower than the short circuit current (I_{sc}).
- **Voltage at Maximum Power Point (V_{mpp}):** represents the voltage produced by the

PV cell when operating at the maximum power point. As shown in figure (I.8), its value is lower than the open voltage (V_{oc}).

✓ Electrical characteristics of photovoltaic cell

The electrical characteristics of a photovoltaic cell can be described by four parameters:

- **<u>Short-circuit current Isc (for Voc= 0)</u>**

The short-circuit current is the maximum current generated by the cell when it is subject to a short-circuit (V = 0) for" full sun" illumination, it is directly proportional to the radiant energy received on the surface of the cell. Its value is obtained by connecting an ammeter across the cell terminals. Since Rs, Rsh, it can obtain Icc = Iph [13].

- **<u>Open circuit voltage Voc (for Isc = 0)</u>**

The open circuit voltage, Voc, refers to the voltage across the terminals of the cell when no load is connected, resulting in a generated current (I) of 0. By neglecting the current flowing through the parallel resistor Rsh, the Voc can be determined by directly connecting a voltmeter to the terminals of the cell [14].

- **<u>Maximum Power Point (MPP)</u>**

The crucial section of the I-V characteristic for users is the one that corresponds to energy generation. This point does not lie at the open circuit voltage (Voc) or the short-circuit point since they do not generate any power. Considering that power is the product of voltage and current (P = V Ö I), the maximum power point (Vmp, Imp) represents the operating point where the power supplied to the load is at its highest [14].

$$P_{mp} = V_{mp} \times I_{mp}$$

Were

P_{mp} = maximum power point.

Vmp = maximum power voltage. Imp= maximum power current.

- **<u>Fill factor (FF)</u>**

It is an important parameter in assessing the performance of a solar cell. It is calculated as the ratio of the maximum power of the solar cell to the product of the open-circuit voltage (Voc) and short-circuit current (Isc). It typically has a value of around 0.7 for efficient cells and decreases with temperature [15].

The expression for the fill factor is given by:

$$FF = \frac{V_{mp} I_{mp}}{U_{oc} I_{cc}} V_{mp}\ I_{mp}$$

Were

Voc = open circuit voltage.

Icc = short circuit current.

2.1.6 Irradiance and Temperature Effect on the I-V and P-V Characteristics

The performance of a photovoltaic device depends on external factors such as solar radiation and temperature, which affect the current-voltage (I-V)

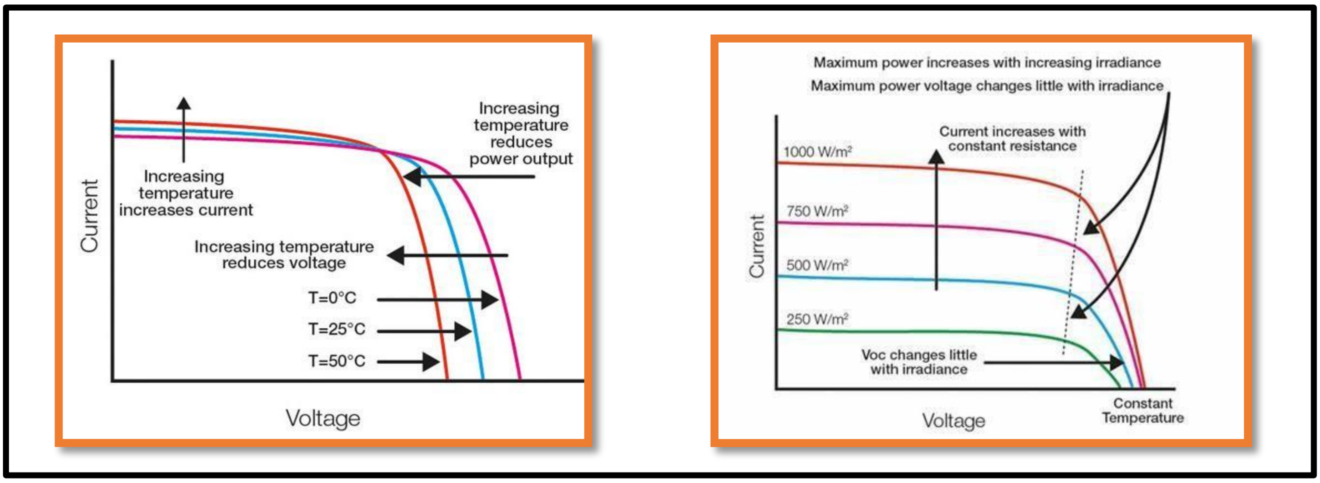
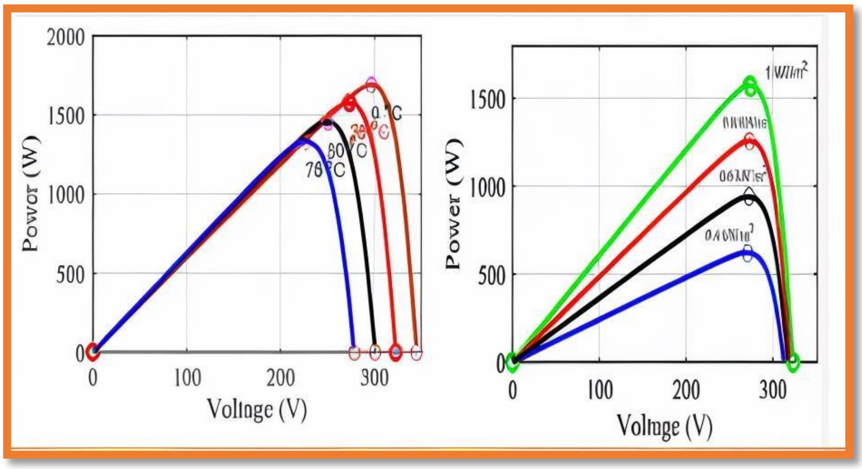


Figure (I. 9): effect of irradiation and temperature change on the I-V curve characteristic of the PV panel [16].

(Figure I. 9) illustrate that as temperature rises, the voltage of the PV device decreases while the current increases slightly. Conversely, with increasing irradiation, the current increases while the voltage slightly decreases. In addition, (Figure I. 10) demonstrates that the power output is directly proportional to the irradiance level and inversely proportional to the temper ature. It also indicates that the maximum power point varies with changes in temperature and



irradiation.

Temperature and irradiance have a direct influence on the electrical characteristics of a photovoltaic module. To show this impact, specific equations are used:

- The light generated current of the photovoltaic cell depends linearly on the solar irradiation and is also influenced by the temperature according to the following equation [18]:

Figure (I. 10): effect of irradiation and temperature change on the P-V curve characteristic of the photovoltaic panel [17].

where $I_{ph,\ n}$ is the light generated current at the nominal conditions (25°C and 1000W/m²) ΔT=T- Tn where T and Tn are the actual and nominal temperature in Kalvin respectively. Gand G_n are the actual and nominal irradiation on the device in [W/m²] respectively.

- The diode saturation current I0 and its dependence on the temperature may be expressed

by:

$$I_0 = I_{0,n} \left(\frac{Tn}{T}\right)^3 \exp\left(\frac{qEg}{ak}\left(\frac{1}{Tn} - \frac{1}{T}\right)\right)$$

Where E_g is the bandgap energy of the semiconductor (Eg≈1.12eV), and $I_{0,n}$ is the nom - inal saturation current:

$$I_{0,n} = \frac{Isc,n}{\exp\left(\frac{Voc,n}{aVt,n}\right)} - 1$$

2.1.7 Modeling of PV cells

2.1.7.1 Modeling of Single-Diode solar cell

Three equivalent circuit models can be used to single-diode model:

- ✓ Ideal solar cell or the single mechanism, three parameters (1M3P) model.
- ✓ Solar cell with series resistance or the 1M4P model.
- ✓ Solar Cell with Series and shunt resistances, also known as the 1M5P model.

✓ **Ideal Solar Cell (1M3P)**

The ideal equivalent circuit of a solar cell is a current source in parallel with a single diode. This model involves three unknown parameters: V (open-circuit voltage), Iph (short-circuit current), and Is (diode saturation current). This model is also known as the 1M3P model.
The configuration of the ideal solar cell model with a single-diode is shown in Figure (I. 12)

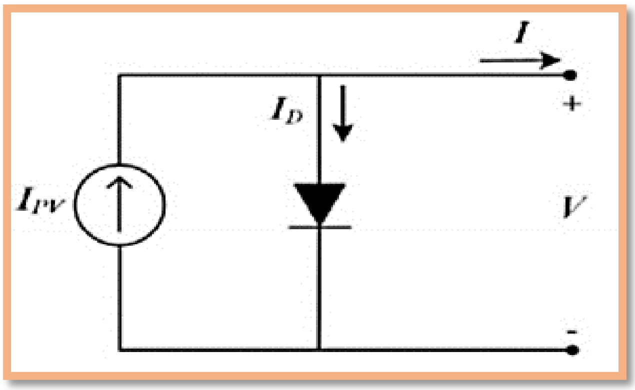


Figure (I .11): circuit the ideal model.

The characteristic equation is deduced directly from the Kirchhoff law

Ipv = Iph × Id

Were

Ipv = photovoltaic current.

Iph =photon current.

Id = diode current.

The diode current is given by the following equation: law:

$$I_d = I_s\left(e^{\frac{qu\,pu}{mkT}} - 1\right)$$

Were

Is = series current.

q = electric charge (1.6*10-19C).

m = diode quality factor, K = Boltzmann constant (1.3854*10-23 J/K). T = temperature.

Vpv = photovoltaic voltage. So, the output current is presented by the following nonlinear equation

$$I_d = I_{ph} - I_s\left(e^{\frac{qu\,pu}{mkT}} - 1\right)$$

For the same irradiation and PN junction temperature conditions, the short-circuit current Isc is the greatest value of the current generated by the cell and the open circuit voltage Voc is the greatest value of the voltage at the cell terminals:

$$I_{sc} = I_{ph} = I_{pu} for V_{pu} = 0$$

$$V_{pu} = V_{oc} = \frac{mkT}{q}\left(1 + \frac{I_{sc}}{I_s}\right)$$

The output power is:

$$P = V_{pu}\left[I_{sc} - I_s\left(e^{\frac{qu\,pu}{mkT}} - 1\right)\right]$$

✓ **<u>Solar Cell with Series Resistance</u>**

More accuracy can be introduced to the model by adding a series resistance. The electric schematic equivalent to this model is shown in Figure (I .13) This model involves the following four unknown parameters (V, Iph, Rs, and Is), which is also called 1M4P [14].

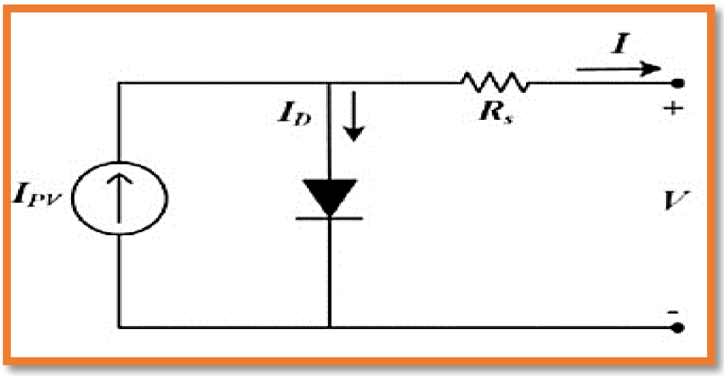


Figure (I .12): Circuit model 1M4P [14].

The diode current is:

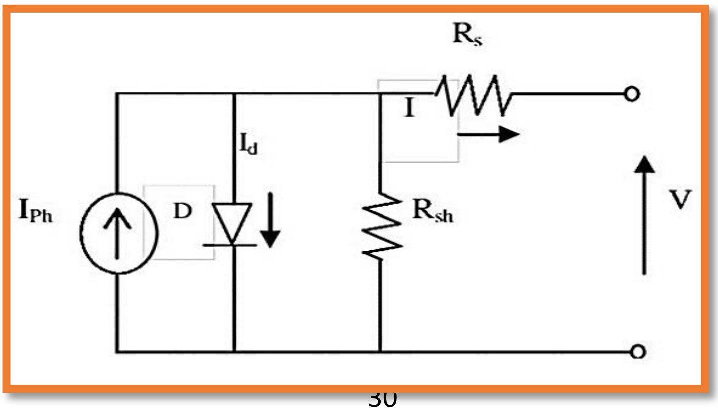
$$I_d = I_s\left(e^{\frac{qu\,pu\,+R_sI_{pu}}{mkT}} - 1\right)$$

Where Rs = series resistance. Therefore, the I-V characteristic of the solar cell with single- diode and series resistance is given by:

$$I_{pu} = I_{ph} - I_s(e^{qu_{pu}+R_sI_{pu}} - 1)$$

✓ **<u>Solar Cell with Series and Shunt Resistances (1M5P)</u>**

The losses in this configuration are modeled by two resistances: shunt resistance and series resistance. Thus, the model involves the following five unknown parameters (V, Iph, Rs, Rsh, and Is). This model is also called 1M5P, and its electrical schematic is shown in Figure (I .14) [20].



The characteristic equation can be deduced directly by using the Kirchhoff law:

$$Ipv = Iph - Id - Ish$$

Were

Ish = shunt current the diode current is:

Figure (I .13): "Circuit of model 1M" [20].

$$I_{sc} = \frac{V + R_s I_{pu}}{R_{sh}}$$

The single-diode model is governed by the following equation:

$$I_{pu} = I_{ph} - I_s(e^{qu_{pu}+R_s I_{pu}} - 1) - \frac{V+R_s I_{pu}}{R_{sh}}$$

Were

Rsh = shunt resistance.

The modeling of the PV cell in the three cases was done by applying the previous equations. Many types of simulation are carried out depending on the chosen model and the selected parameters [20].

- ✓ **Modeling of two-diodes solar cell**

The two-diode model of the solar cell provides a high level of accuracy, although it is somewhat more complex. The configuration of this model is shown in Figure (I .15) [21].

The two-diodes model is governed by the following equation

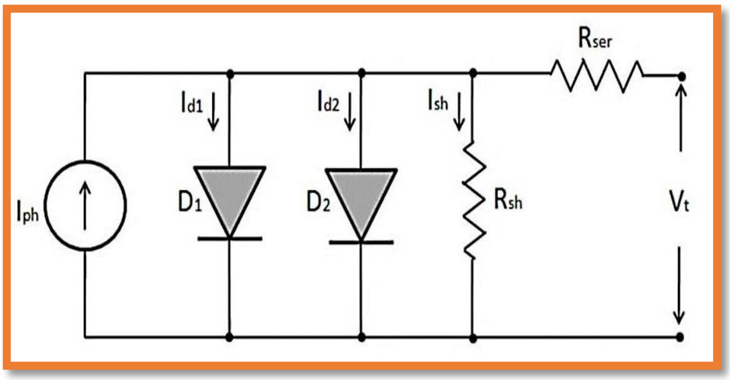


Figure (I .14): Equivalent circuit of two diodes model [21].

$$I_{pu} = I_{l.ph} - I_{1.pu}\left(e^{\frac{u_{pu}+R_s I_{pu}}{ut1}} - 1\right) - I_{2.pu}\left(e^{\frac{u_{pu}+R_s I_{pu}}{ut2}} - 1\right) - \frac{V_{pu} + R_s I_{pu}}{R_{sh}}$$

Were

I02 = first diode saturation current 1.

I02 = two diode saturation current.

Vt2 = the instant temperature voltage.

2.1. 8 Types of PV Systems

Depending on how the energy is used, there are three different types of PV systems: standalone systems, hybrid systems, and Grid-Connected systems [22].

2.1.8.1 Standalone Systems

A standalone PV system is an installation that operates independently of the electrical grid or any other energy sources. This system is used to supply power to one or more consumers, such as houses, cabins, or camps in remote areas, as well as for applications like monitoring and water pumping.

There are two types of standalone PV systems: with storage and without storage. The general schematic of a standalone PV system is shown in Figure (I .16) [23].

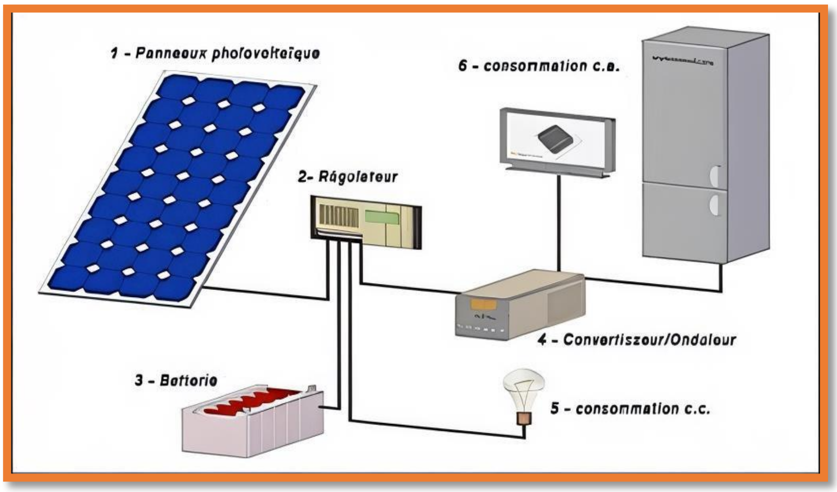


Figure (I .15): Standalone PV system with battery [22].

2.1.8.2 Hybrid PV Systems

Hybrid PV systems integrate a PV generator with another power source, such as wind turbines, diesel generators, hydroelectric systems, or even the public electricity grid. These systems are particularly suitable for remote locations where having electricity at all times is crucial, where fuel transportation costs are high, or where using a standalone PV system with batteries is not yet cost-effective [22].

They are often used for critical and strategic applications, such as telecommunication relays, border posts, and isolated housing, where conventional electricity grids are unavailable [23]. A hybrid system is illustrated in Figure (I .18).

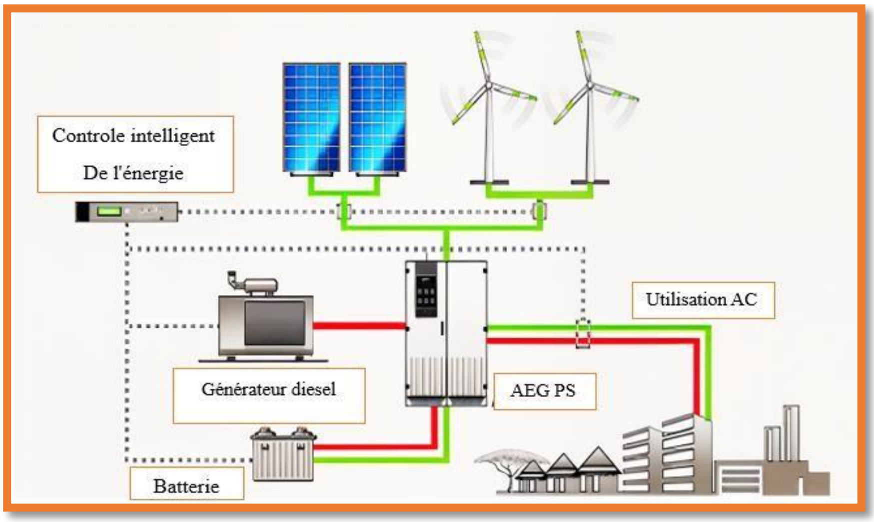


Figure (I .16): Hybrid PV system [22].

2.1.8.3 Grid-Connected Systems

In these PV systems, the PV generator is directly connected to the electrical grid. The grid- connected PV system is equipped with power converters to adapt the energy produced by the PV panels. These converters consist of a chopper with an MPPT, a filter, an inverter, and appropriate electronics to ensure voltage and frequency adaptation with the grid. The structure of a Grid-Connected PV system is shown in Figure (I .19) [24].

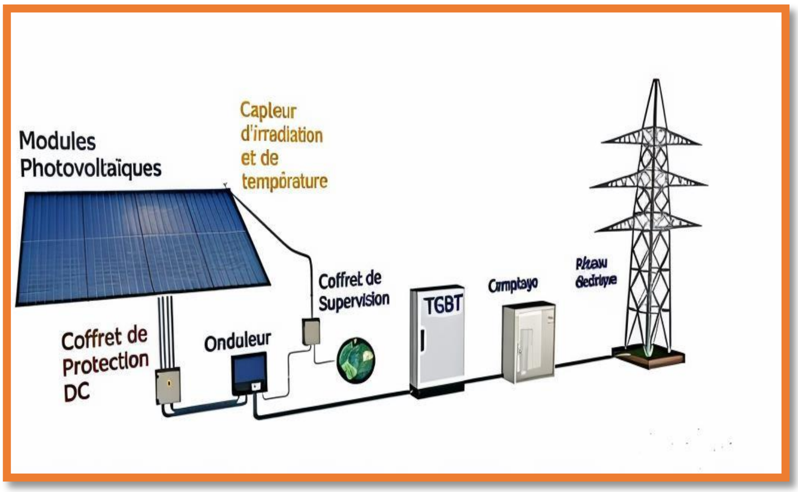


Figure (I.17): Structure of a Grid-Connected PV system [22].

The major advantage of this solution is the absence of batteries. Energy is no longer stored; instead, it is directly injected into the local grid, which supplies houses at night or during cloudy days. This ensures that all the energy is utilized. There is a meter that runs in one direction for consumption and another in the opposite direction for production.

These systems do not serve as backup power sources in the event of a grid outage, as they do not have any energy reserves [24]. In our study, we focus on the operation of a Grid-Connected PV system.

2.1. 9 General Presentation of the Photovoltaic Chain

Photovoltaic generation systems are among the most promising renewable energy technologies due to their numerous advantages.

In most cases, impedance matching must be achieved by inserting an electronic device between the generator and its electrical load. This device ensures that the system operates at its maximum power [25]

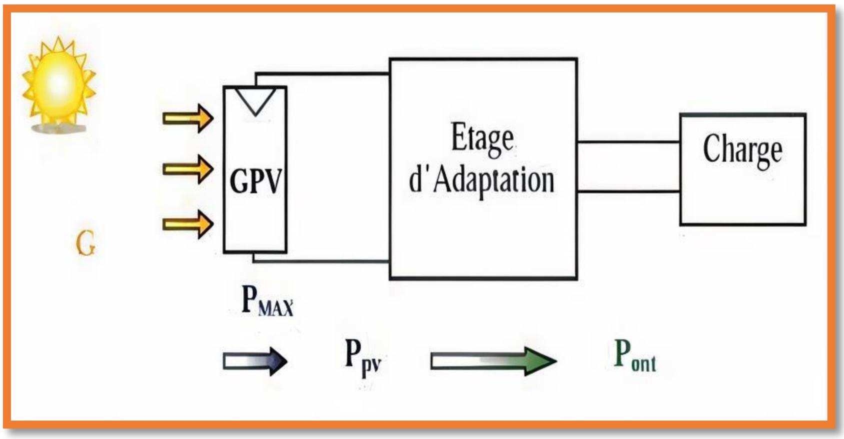


Figure (I.18): General Structure of a Photovoltaic Conversion Chain [26].

2.1.9.1 Off-Grid Installations

In the case of off-grid installations, the energy produced by photovoltaic solar panels is either used immediately (for pumping, ventilation, etc.) or stored in batteries for later use. The generated direct current (DC) can directly power devices designed for this purpose or be converted into 230V alternating current (AC) [27].

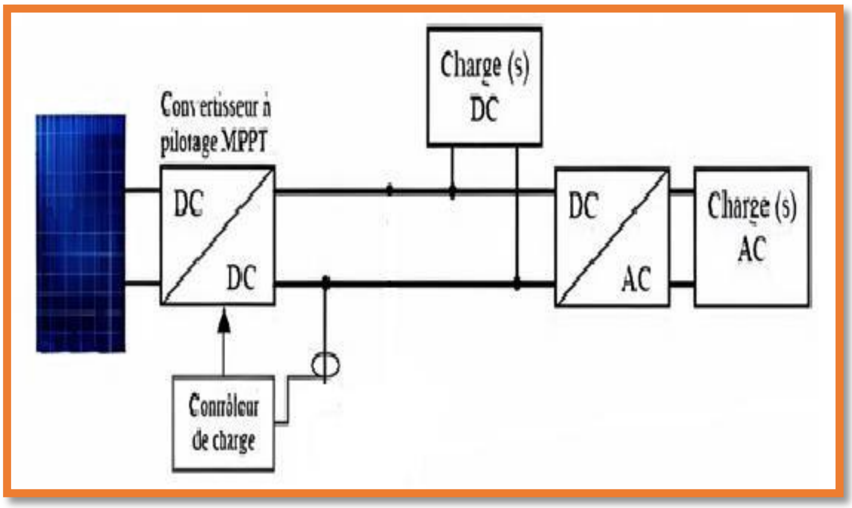


Figure (I.19): Off-Grid Photovoltaic Installation [27].

2.1.9.2 Grid-Connected Installations (On-Grid)

The system can also be connected to the electrical grid. The main advantage of grid connection is eliminating the need for costly and complex electricity storage.

In its most economical versions, the inverter operates only in the presence of the grid; thus, a power outage renders the renewable energy generation system inoperative. A bidirectional inverter is required if a DC load is present.

If local consumption exceeds the power generated by the photovoltaic system, the grid supplies the additional energy needed. Conversely, when production surpasses consumption, the excess energy is fed into the public grid to supply nearby consumers [27].

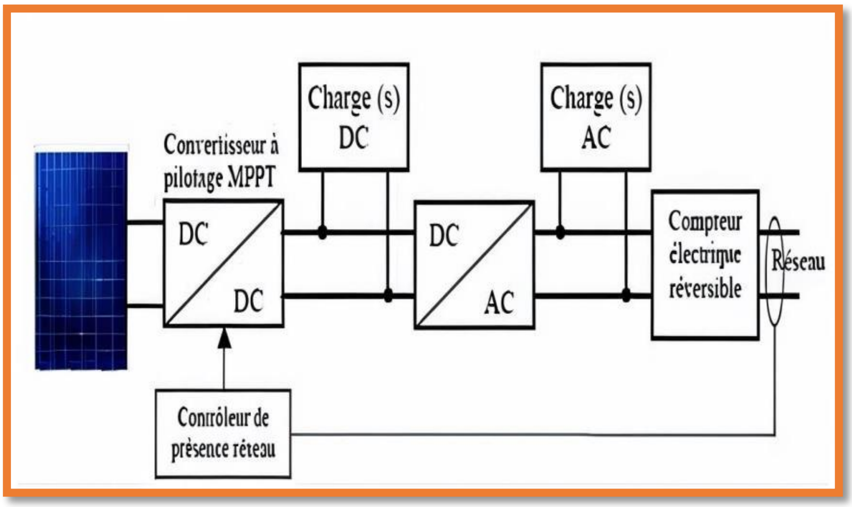


Figure (I.20): Grid-Connected Photovoltaic Installation [27].

2. 2 Photovoltaic Generator

The basic photovoltaic cell serves as a very low-power generator compared to the energy demands of most domestic and industrial applications. A single elementary cell, measuring a few tens of square centimeters, typically delivers at most a few watts, with a voltage below one volt, which is generally determined by the PN junction voltage.

To generate more power, multiple cells must be assembled to form a complete photovoltaic module (energy generator) [28].

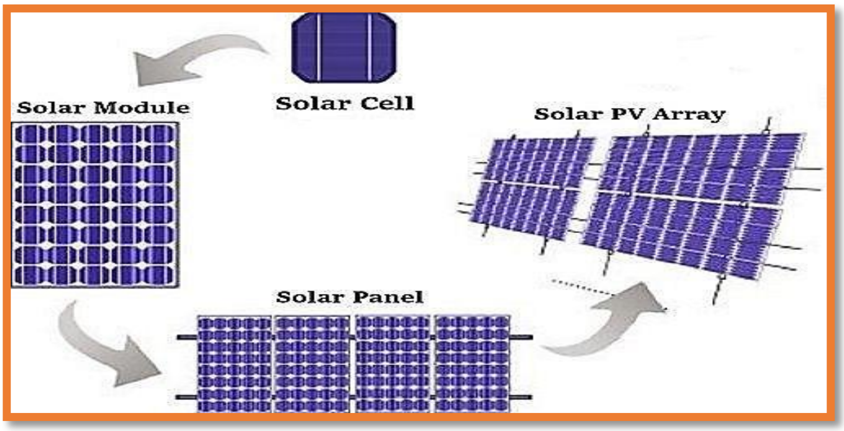


Figure (I.21): Representative Diagram of a Cell, a Module,

2. 3 Energy Storage

In a photovoltaic installation, storage refers to the conversion of energy produced by the photovoltaic generator, keeping it available for later use. Managing solar energy requires considering storage based on weather conditions.

There are two types of storage: [30]:

- Short-term storage: Storage duration of less than 10 minutes.
- Long-term storage: Storage duration of more than 10 minutes.

2. 3.1 The Battery

The cell is the basic electrochemical unit used to generate electrical energy from stored chemical energy or to store electrical energy in the form of chemical energy. It consists of a positive electrode and a negative electrode in a container filled with an electrolyte, which provides the essential ionic conductivity between the positive and negative electrodes of a cell. A separator, which is an ion-permeable and electronically non-conductive material or spacer, prevents short circuits between the positive and negative electrodes of the cell [31].

The desired battery is obtained when two or more cells are connected in a suitable series/parallel arrangement to achieve the required operating voltage and capacity for a specific load.

2. 3. 2 The Role of Batteries in a PV System

A battery is generally required when the PV grid cannot operate, for example, at night or during cloudy weather. The main functions of a storage battery in a PV system are as follows [32]:

- Energy storage capacity and autonomy
- Voltage and current stabilization

2. 3. 3 Principle of Battery Operation

Two electrodes immersed in an electrolyte form an electrochemical chain. Metal plates of different types can, for example, serve as electrodes.

The electrochemical chain acts as a current generator by converting chemical energy into electrical energy. It is at the electrodes that electrochemical reactions take place. These reactions can generally be described as follows [30]:

At the anode, which is the negative electrode, oxidation occurs during discharge, characterized by the following formula:

$$M_1 \rightarrow M_1^{n+} + ne^-$$

M1 being the active species of the anode.
The released electrons will travel through the external circuit to reach the cathode, which is the positive electrode, where the reduction reaction takes place.

$$M_2^{n+} + 2e^- \rightarrow M_2$$

The overall redox reaction is as follows:

$$M_1 + M_2^{n+} \rightarrow M_1^{n+} + M_2$$

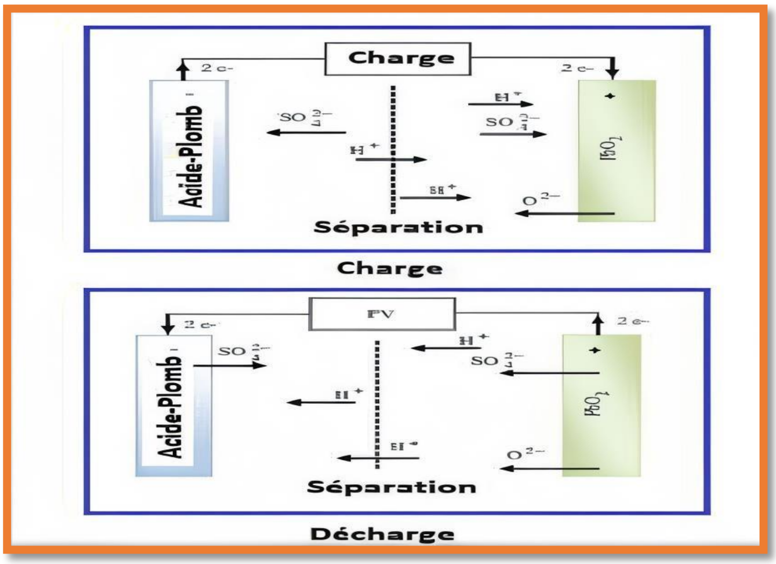


Figure (I.22): Principle of Operation of a Lead-Acid Battery [32].

2. 4 The Different Connections of PV Panels

2.4.1 Series Connection

- **How it works:** The solar panels are connected together so that the positive and negative terminals of each panel are connected to the next one.
- **Result:** The voltage increases, but if one panel is shaded or damaged, it can affect the performance of all the panels.

2.4.2 Parallel Connection

- **How it works:** The panels are connected so that all the positive terminals are connected together, and all the negative terminals are connected together.
- **Result:** The current increases. This method allows for higher current without significant effect if one panel is shaded.

2.4.3 Hybrid Connection

- **How it works:** A combination of both series and parallel connections. Both voltage and current can be increased together for better performance.

- **Result:** You get the benefits of both methods together, but the system design may become more complex.

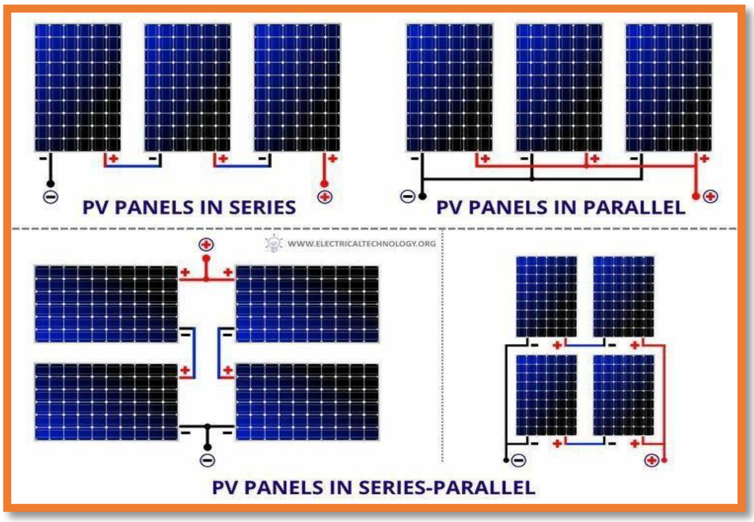


Figure (I.23): Series, Parallel & Series-Parallel Connection of PV Panels.

2. 5 Advantages and disadvantages of photovoltaic systems

Photovoltaic systems offer numerous advantages, but they also have certain drawbacks, which are discussed in the following subsections [33]:

2. 5 .1 Advantages

- ❖ Direct conversion of free and inexhaustible solar energy into electricity.
- ❖ Absence of noise, pollution, and emissions, along with reduced maintenance requirements (no moving parts and individual module lifespan of approximately 20 years).
- ❖ Flexibility to adjust the installation size according to current needs, with the option of expansion as energy requirements increase.
- ❖ Photovoltaic systems provide added value to rural areas, particularly in developing countries where no electricity grid is available.
- ❖ Ensured profitability for low-power applications (less than 3-5 kWh/day).

2. 5 .2 Disadvantages

- The manufacturing of photovoltaic modules requires advanced technology and substantial investments.
- Photovoltaic generators are primarily competitive with diesel generators for low energy demands in isolated areas.
- Incorporating electrical energy storage in the form of batteries increases the cost of the photovoltaic system. However, proper selection of batteries and associated regulation components ensures reliability and performance.
- Many devices available in the market operate on alternating current at higher voltages (220-230V), whereas the power generated by the photovoltaic system is unidirectional and low voltage (<30V). Therefore, a boost/inverter conversion is required.
- High-power photovoltaic systems often require a backup system, such as a wind or diesel generator, to meet periods of high demand or during cloudy weather conditions.

It is important to consider both the advantages and disadvantages of photovoltaic systems to make informed decisions regarding their implementation. While they offer clean and renewable energy solutions, certain limitations and considerations must be taken into account to ensure optimal performance and cost-effectiveness [34].

Conclusion

In this chapter, we introduced the fundamental concepts of photovoltaic (PV) systems. We began by explaining the nature and importance of solar energy, followed by the working principle of photovoltaic conversion. A detailed classification of PV cells was presented, highlighting their structures and electrical characteristics. Additionally, we explored the main types of PV systems and their configurations, including series, parallel, and hybrid connections. The advantages and limitations of each configuration were also discussed to provide a comprehensive understanding of their practical applications. This foundational knowledge sets the stage for the next chapter, which focuses on the extraction of maximum power from PV systems through MPPT techniques.

Chapter II

Maximum Power Point Tracking of PV system

Introduction

Grid-connected photovoltaic (PV) systems play a crucial role in modern distributed energy networks by providing clean and sustainable electricity. As the deployment of PV installations continues to grow, the performance demands on inverters increase. These inverters must be cost-effective, lightweight, and compact to suit residential applications, while also ensuring high reliability to match the longevity of PV panels. Additionally, they must achieve efficient power conversion and comply with safety standards under diverse environmental conditions.

This chapter presents a comprehensive overview of Grid-Connected PV system modeling and configuration. It includes a review of common PV inverter topologies and focuses on the operation of a Boost Converter integrated with a Maximum Power Point Tracking (MPPT) controller. This arrangement is used to evaluate the effectiveness of the MPPT technique and analyze the power output of the PV system under varying levels of solar irradiance and ambient temperature.

1. Modeling of a PV Cell

An individual solar cell can be represented as part of an electrical circuit, incorporating two resistors—one in series and one in parallel—that account for Joule losses and recombination effects. It also includes a **p–n** junction, known as a diode, along with a photocurrent generator that describes the conversion of light into electrical current. This configuration is referred to as the single-diode solar cell model [KRS 18].

Figure (II.1) illustrates the ideal representation of a photovoltaic (PV) cell. The current source Iph represents the photocurrent generated by the incident solar radiation, while Rp and Rs correspond to the intrinsic parallel and series resistances of the cell, respectively. Since Rp is typically very large and Rs is very small, they can be neglected to simplify the analysis without significantly affecting the accuracy of the model.

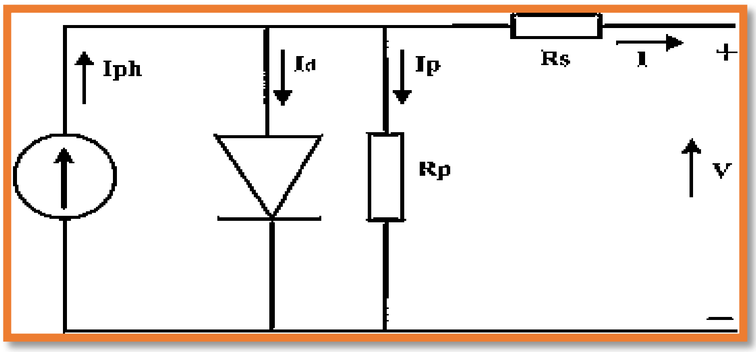


Figure (II.1): Model of a PV cell.

2. **Characterization of the PV Module**

The **KC200GT** photovoltaic module was analyzed to determine its electrical characteristics and performance under standard operating conditions. It consists of **54** monocrystalline silicon solar cells, each measuring **125 × 125 mm**, connected in series to ensure consistent energy distribution across the module.

This module is capable of delivering a peak power of **200 watts** at **32 volts**, making it suitable for various solar applications. The characterization process involved examining its power-voltage and current-voltage relationships under a solar irradiance of **1000 W/m²**, allowing for a detailed assessment of its operational efficiency and response to varying environmental conditions

The electrical characteristics of the KC200GT photovoltaic module under standard test conditions are presented in Table (II.1).

Total number of cells in series (N_s)	54
Rated power (W)	200.143 W
Short-circuit Current (I_{sc})	8.21 A
Open circuit voltage (V_{oc})	32.9 V
Current at Maximum power (I_{mp})	7.61 A
Voltage at Maximum power (V_{mp})	26.3 V

Table (II.1): Electrical properties of the KC200GT PV module under standard test conditions.

3. Simulation of the PV Module

Based on the mathematical model of the solar cell developed using the MATLAB / SimPowerSystem tool, the schematic block in SIMULINK is presented in Figure (II .2)

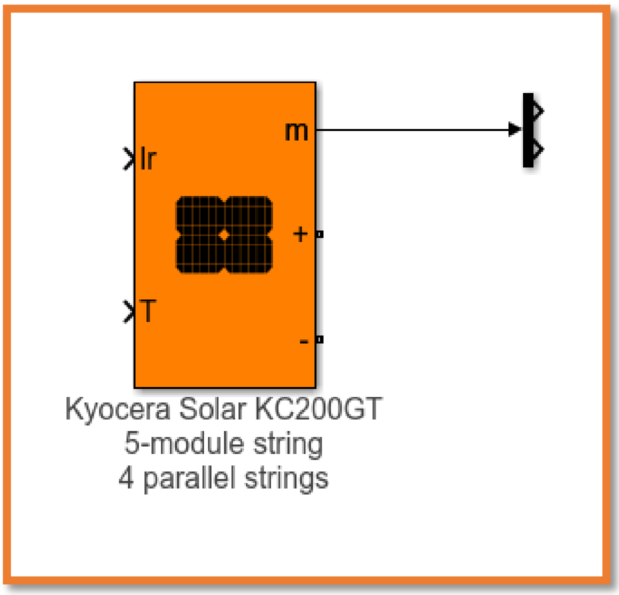


Figure (II .2):" Block diagram of the solar

To increase the output power, PV modules are interconnected within a panel.
In this configuration, modules can be connected in series, in parallel, or both. In our case, the number of series-connected modules is NS = 5, while the number of parallel-connected modules is NP = 4.

To analyze the influence of irradiance, we fix the temperature at T = 25°C and vary the irradiance over a sufficient range.

According to Figure (II .3), a significant decrease in short-circuit current is observed with decreasing irradiance (E), while the open-circuit voltage experiences only a minor reduction.

This demonstrates that the short-circuit current of the cell is directly dependent on irradiance, whereas the open-circuit voltage undergoes a slight increase as irradiance varies from 200 W/m² to 1000 W/m².

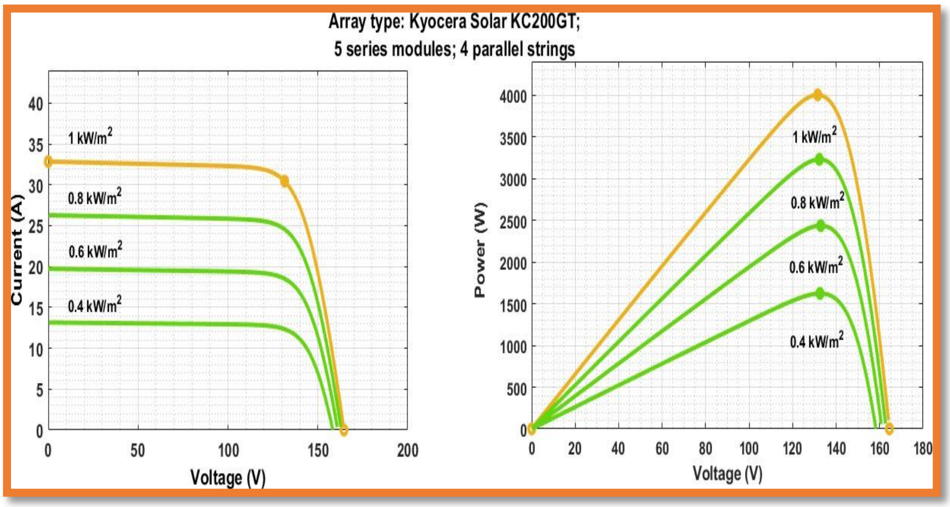


Figure (II .3): Simulation results of the Current-Voltage.

We also notice from Figure (II .3) that irradiance proportionally influences the power and open-circuit voltage of the PV generator.

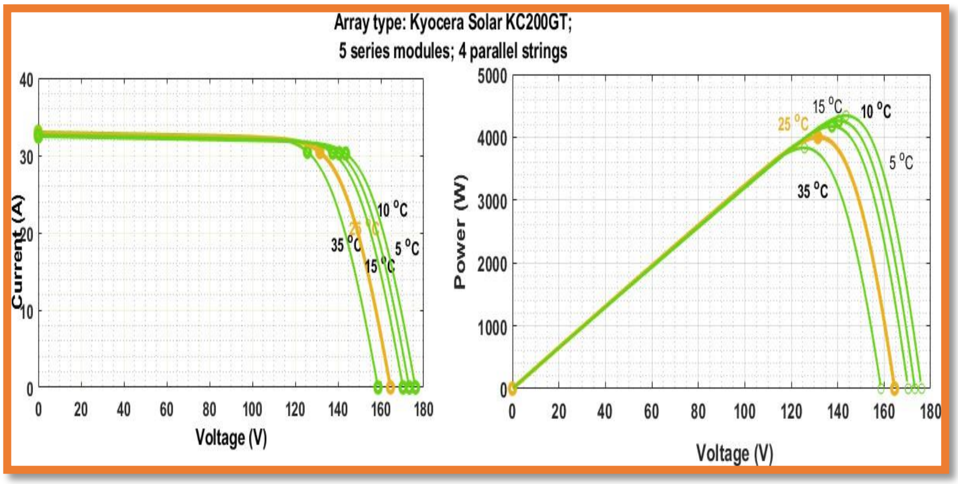


Figure (II .4): Simulation results of the Current-Voltage characteristics for various temperatures and an irradiance of E=1000 W/m2.

Figure (II .6) shows that, in contrast to the short-circuit current, which stays constant, the PV generator's open-circuit voltage decreases as the temperature rises.

A PV cell's physical behavior in response to temperature and irradiance changes is accurately reflected by the selected model, which has produced results that are in line with those found in the literature.

4. DC-DC Converters in Photovoltaic Systems

a) Definition and Importance of Static Converters

Static converters are power electronic devices based on semiconductor technology, designed to convert electrical energy into a suitable form for powering various types of loads. These converters play a crucial role in regulating voltage and/or frequency to ensure compatibility between the generated power and the electrical system, using specialized energy management components and switching devices.

To achieve efficient power conversion, it is essential to minimize energy losses, particularly heat dissipation, which can negatively impact system performance and lead to overheating of electronic components. To address this challenge, modern static converters employ energy storage elements, such as inductors and capacitors, alongside semiconductor switches that precisely control and regulate the flow of electrical power

The selection of switching devices depends on the system's power level requirements:

- ✓ **MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistors):** Used in low-power applications (up to a few kilowatts), providing high efficiency and fast switching capabilities.
- ✓ **IGBTs (Insulated-Gate Bipolar Transistors):** Commonly utilized in medium-to-high power systems due to their optimal balance between conduction efficiency and switching performance.
- ✓ **Thyristors:** Ideal for very high-power applications, where robust voltage and current control is necessary for system stability.

b) Role of DC-DC Converters in PV Systems

DC-DC converters are essential components in photovoltaic (PV) systems, responsible for regulating voltage and current levels to maximize energy extraction from solar panels.

These converters modify the electrical output of the PV array to align with the requirements of subsequent components, such as inverters or direct DC loads, thereby enhancing overall system efficiency and operational stability.

Among various DC-DC converter types, the Boost Converter is one of the most widely used in PV applications due to its ability to increase the relatively low voltage generated by solar panels to the higher levels required for grid connection or standalone power applications.

When integrated with Maximum Power Point Tracking (MPPT) algorithms, DC-DC converters not only optimize energy transfer but also ensure reliable operation under dynamic environmental conditions, such as fluctuations in solar irradiance and temperature.

c) Boost Converter

➢ Definition and Role

A Boost Converter is a DC-DC power conversion device designed to increase the voltage level of a DC source efficiently. It enables electrical energy conversion from a lower input voltage to a higher output voltage, making it ideal for applications such as photovoltaic systems and battery-powered devices.

- **Core Components of a Boost Converter**
  - **Inductor:** Stores and transfers energy during switching cycles.
  - **Switching Transistor (K):** Regulates energy transfer and controls voltage output.
  - **Diode:** Prevents reverse current flow to maintain stability.
  - **Capacitor:** Filters and stabilizes the output voltage to ensure smooth operation.

Also referred to as a Parallel Chopper, the fundamental circuit operation of a Boost Converter is illustrated in Figure (II .7)

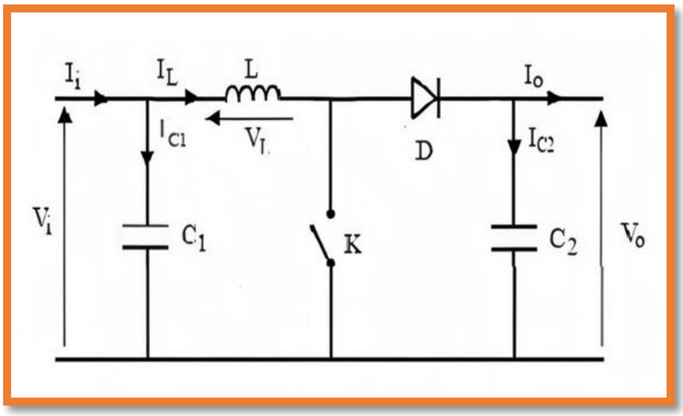


Figure (II .5): Boost Converter Schematic Diagram.

After understanding the operating principle and fundamental design of the Boost Converter, the next section will analyse its performance through simulation using MATLAB-Simulink, where the impact of the duty cycle on energy efficiency and system stability will be evaluated."

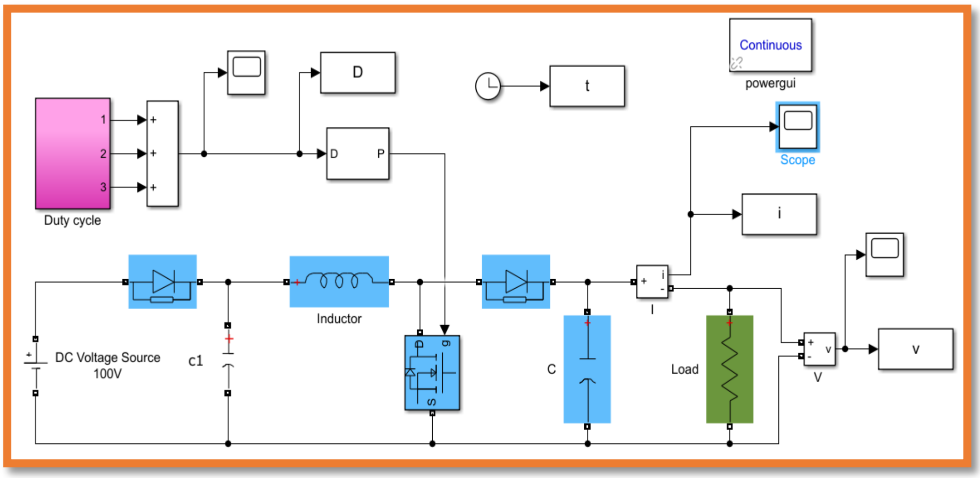


Figure (II .6): SIMULINK implementation of DC/DC Boost converter.

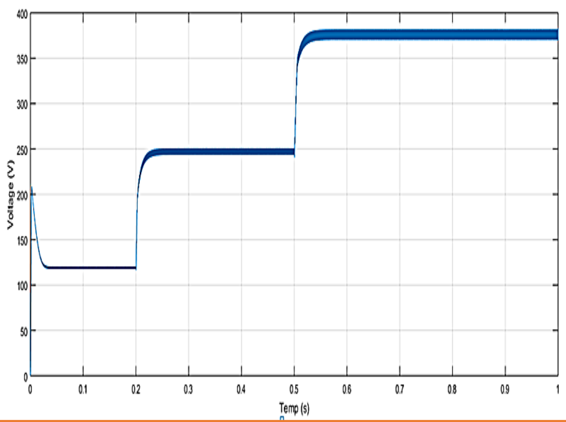


Figure (II .7): "Output voltage of a DC-DC converter."

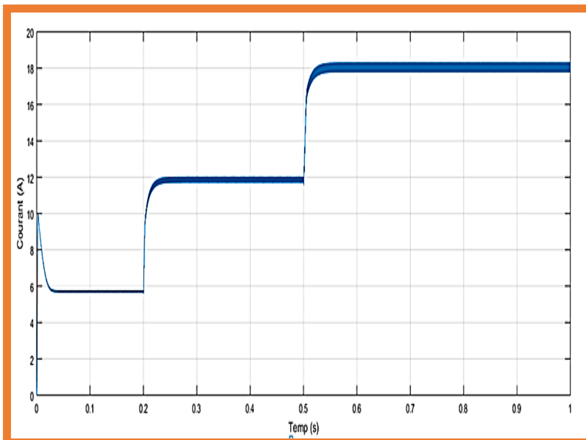


Figure (II .8): "Output current of a DC-DC converter".

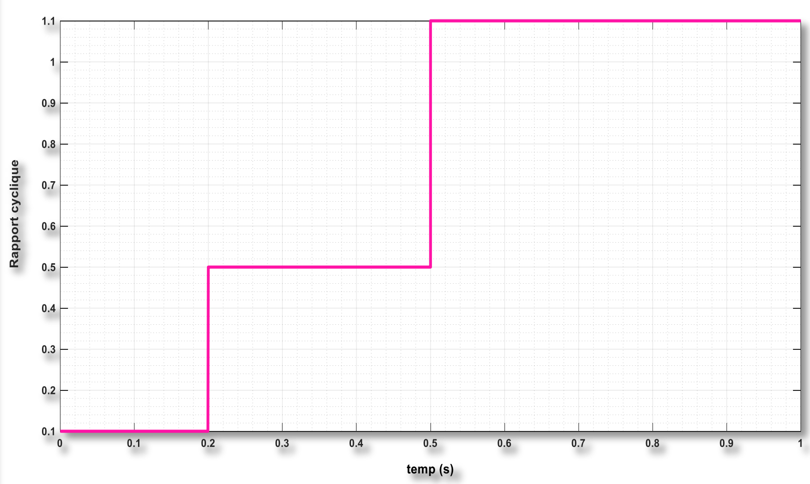


Figure (II .9):" Duty cycle of a DC-DC converter"

The figures ((II .9) and (II .10) and (II .11)) present the simulation results of Boost Converters based on the parametric variation of the duty cycle, as illustrated in Figure (II.8).

A slight oscillation is observed at startup, lasting approximately 0.01 seconds before stabilizing at a certain value. The results further demonstrate the direct relationship between duty cycle variations, where an increase leads to higher current levels and output voltage.

Thus, the Boost Converter performed correctly without failure, as its output voltage is consistently higher than the input voltage, validating its expected functionality.

5. Maximum Power Point Tracking (MPPT):

The maximum power point (MPP) represents the specific operating condition at which solar panels achieve their highest power output. This point is primarily influenced by variations in temperature, fluctuations in irradiance, and load changes over time. The output voltage and current of the photovoltaic modules determine the maximum power output.

Maximum Power Point Tracking (MPPT) is an advanced control method widely utilized in solar power systems to optimize energy extraction. To ensure maximum power transfer, MPPT dynamically adjusts the power interfaces to align the operational characteristics of the load with those of the photovoltaic array.

6. Operating Principle of MPPT:

The Maximum Power Point Tracking (MPPT) technique is a control mechanism designed to ensure that a photovoltaic (PV) module operates at its optimal power point, maximizing energy extraction. The fundamental concept behind MPPT is the continuous tracking of the Maximum Power Point (MPP) by dynamically adjusting the electrical operating conditions of the PV generator to optimize power transfer to the load.

MPPT is typically implemented using a DC-DC converter, which regulates the electrical power extracted from the solar panels to ensure that the output voltage aligns with the system's operating requirements. The location of the MPP is primarily determined by two key parameters: voltage and power, both of which are influenced by environmental factors such as solar irradiance and temperature.

These parameters are continuously monitored and processed within a feedback control loop, which dynamically adjusts the operation of the converter. This allows the PV system to operate as close as possible to its maximum power point, ensuring efficient performance even under varying weather conditions

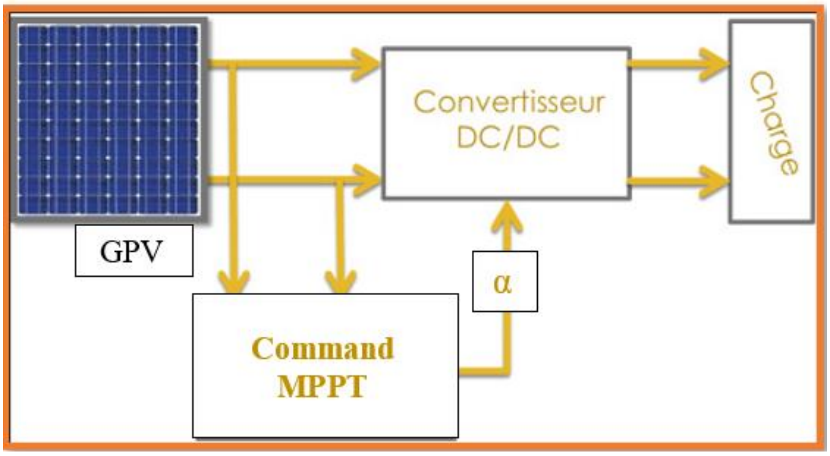


Figure (II .10): "Basic Photovoltaic Conversion Chain"

7. **Classification of MPPT Algorithms**:

To visually represent the classification of MPPT algorithms, Figure 11 illustrates the different categories, helping to distinguish between conventional and intelligent approaches to maximum power point tracking

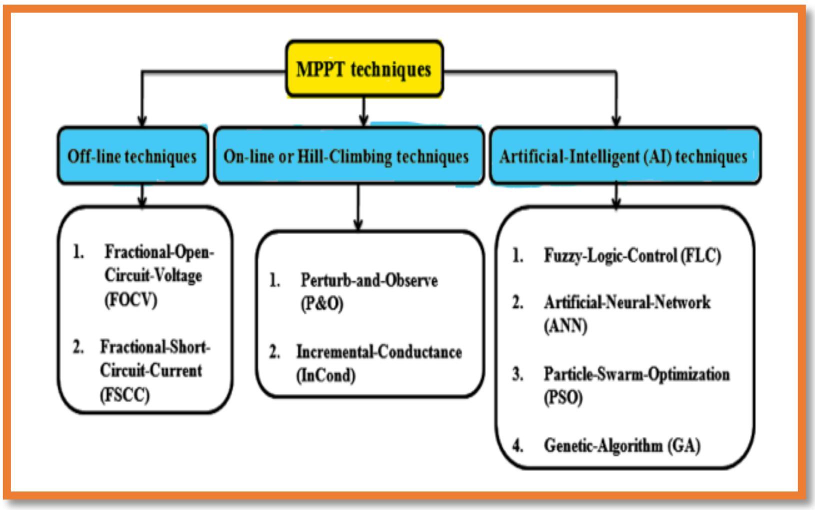


Figure (II .11): "Classification of MPPT Algorithms"

Figure (II .13) presents the classification of MPPT algorithms, dividing them into two main categories: conventional and intelligent techniques. Conventional methods rely on basic mathematical principles but may experience oscillations around the maximum power point. In

contrast, intelligent algorithms utilize advanced strategies such as artificial intelligence and evolutionary optimization to ensure faster and more precise tracking

Adaptability to Environmental Changes	Computational Complexity	Response Speed	Tracking Accuracy	Algor ithm
Weak	Low	Medium	Medium	P&O
Moderate	Medium	Medium	High	INC
Excellent	High	Very Fast	Very High	ANN
Very Good	High	Fast	High	GA
Excellent	Moderate to High	Very Fast	High	FLC

Table (II.2): "Comparison of MPPT Algorithms."

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While conventional MPPT methods offer simplicity and low computational cost, intelligent techniques provide adaptive learning capabilities, ensuring superior performance under dynamic environmental conditions. The choice of an MPPT algorithm depends on a balance between accuracy, speed, and complexity, making advancements in artificial intelligence a crucial factor in optimizing photovoltaic energy extraction.

8.Perturb and Observe (P&O) Method

It is the most widely used MPP tracking algorithm, and as its name suggests, it is based on system perturb ectly on the duty cycle of the chopper, followed by observation of its effect on the panel's output power. If the current panel power **P(k)** is greater than the previous power

P(k-1), the same perturbation direction is maintained; otherwise, the perturbation from the previous cycle is reversed.

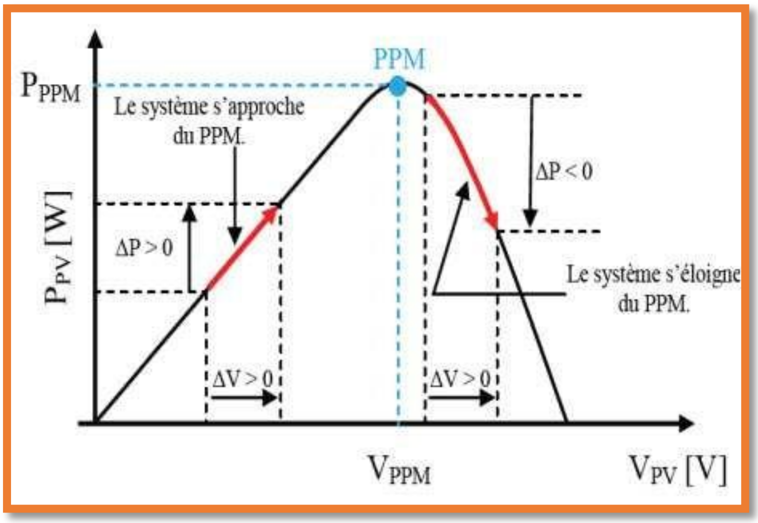


Figure II.12: Characteristic and Operation of the Perturb and Observe Method

Once the MPP is reached, V oscillates around the optimal operating voltage Vmpp. This causes a power loss that depends on the step size of a simple perturbation **Cp**, whose ideal value depends on the system and is determined experimentally.

- If **Cp** is large, the MPPT algorithm will respond quickly to sudden changes in operating conditions, but losses will increase in stable or slightly changing conditions.
- If **Cp** is very sm … will be reduced, but the system will r … ature or irradiation.

✓ **Disadvantage of the Method:**

If sunlight increases suddenly, the panel's power will rise. The algorithm interprets this increase as a result of the previous perturbation and continues in the same direction, moving away from the maximum power point. This process continues until sunlight stabilizes, at which point the maximum power point is reached. This causes a response delay during sudden changes in operating conditions, leading to power losses.

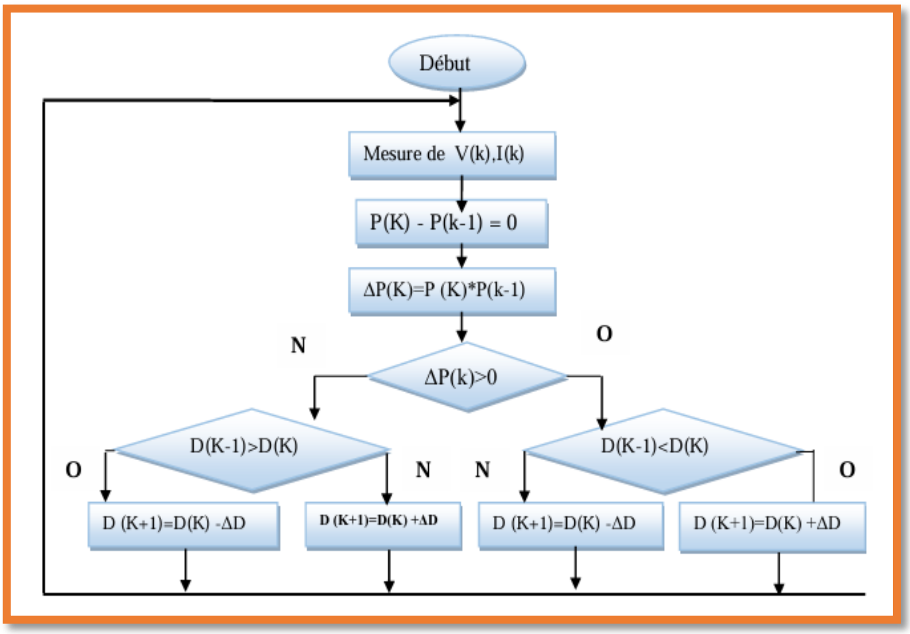
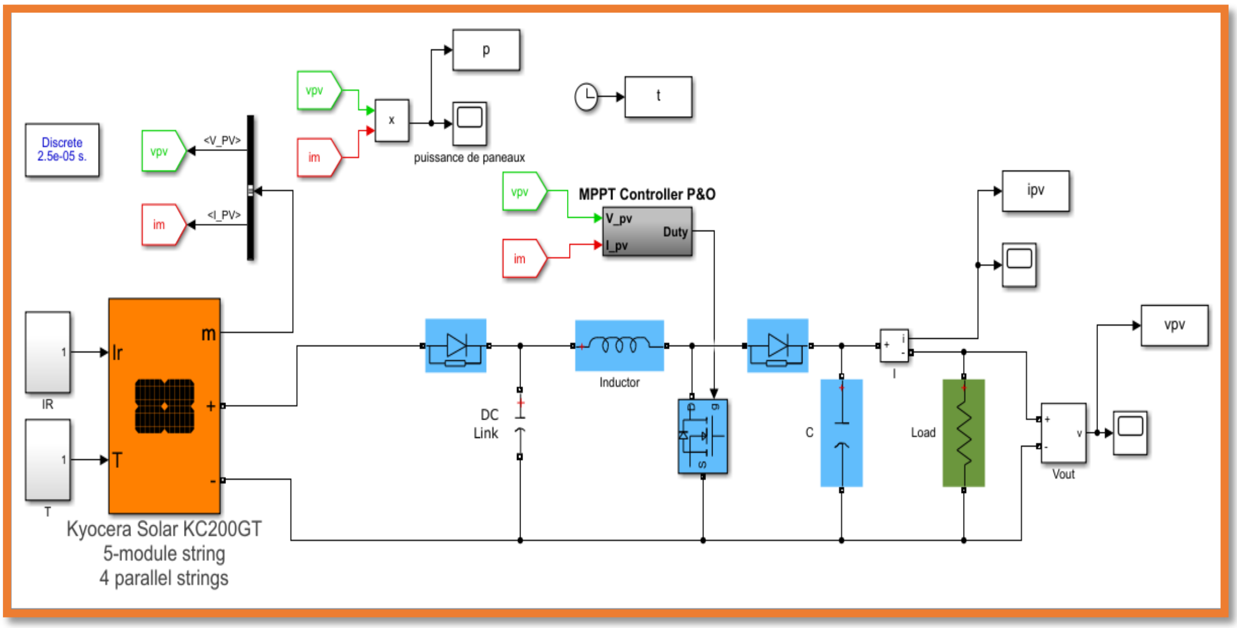


Figure (II .13): Perturbation and Observation (P&O) Algorithm

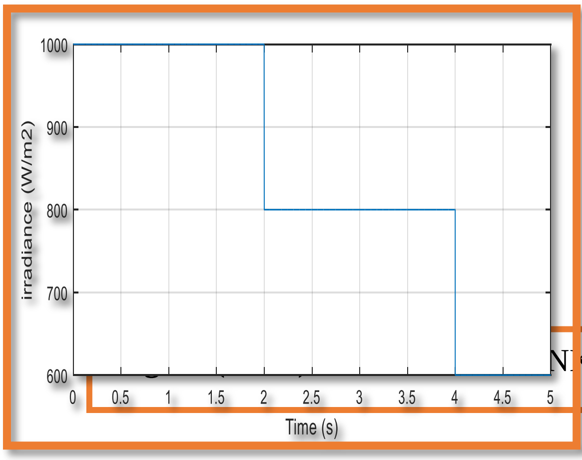
9 .Simulation of the "P&O" MPPT Control:

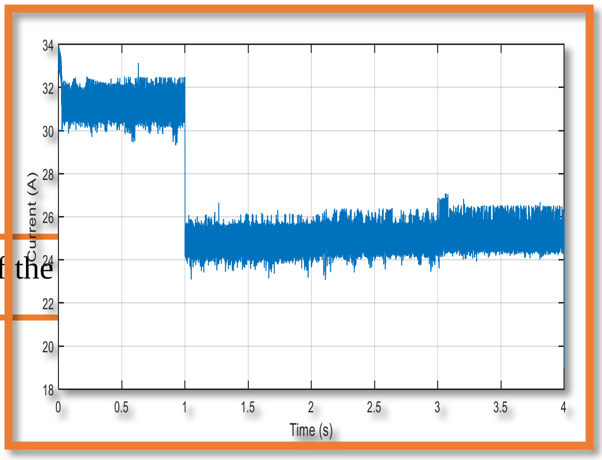
Simulation plays a crucial role in analyzing the performance of solar energy systems, providing an experimental environment to assess various parameters without the need for costly physical implementation. In this section, the "Perturb and Observe" (P&O) MPPT technique will be simulated using MATLAB/Simulink to evaluate the system's efficiency and responsiveness to variations in solar irradiance and electrical load.

Through this simulation, the real-time performance of the MPPT algorithm can be monitored, demonstrating how voltage and current adjustments maximize power extraction from photovoltaic panels. This analysis helps refine the design of solar energy systems, enhancing their operational efficiency



10.Simulation Results:





The PV system with MPPT was evaluated through MATLAB/Simulink testing under different irradiance levels [1000 W/m²; 800 W/m²; 600 W/m²] at a constant temperature of T = 25°C.

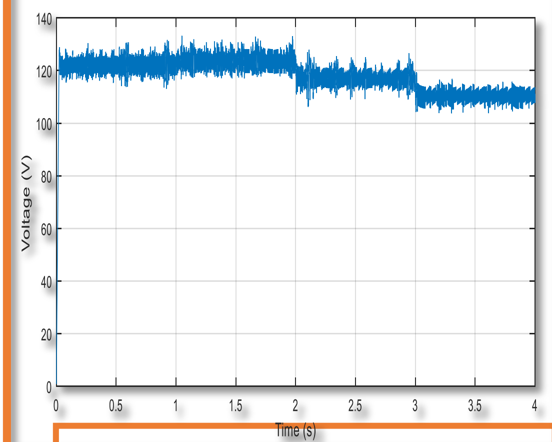


Figure (II .15): "Irradiance Variation Over Time."

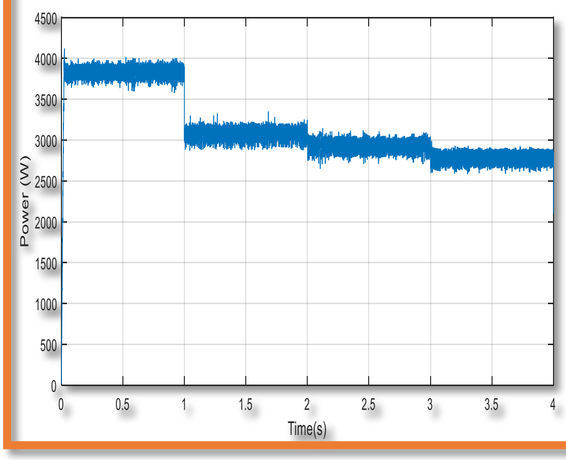


Figure (II .18): Power Variation Over Time.

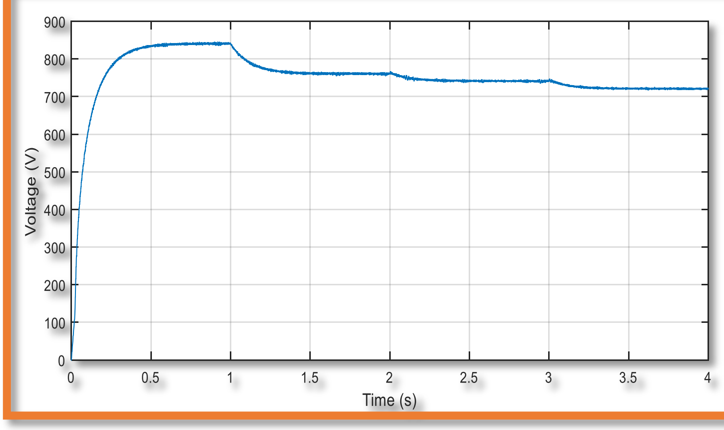


Figure (II .21) illustrates the perfect MPPT operation under irradiance step changes while maintaining a constant temperature. The figure shows that the captured PV power varies between 12 kW and 6 kW, corresponding to the maximum power points.

Conclusion

This chapter analyzed the P&O MPPT algorithm integrated with a DC-DC boost converter, emphasizing its role in optimizing photovoltaic energy extraction. The mathematical modeling of the PV array was examined alongside the MPPT algorithm, demonstrating the system's operational behavior under varying conditions.

The P-V and V-I curves obtained through MATLAB simulations illustrate the dependence of photovoltaic performance on temperature and irradiance variations. The results confirm that the PV system consistently operates near maximum efficiency, maintaining stability around the MPP point despite sudden fluctuations in solar irradiation and ambient temperature

chapter III

Controlled of Three-Phase Grid-Connected solar PV System

Introduction

The continuous rise in global electricity demand, coupled with the rapid depletion of fossil fuel reserves, has intensified efforts to develop sustainable energy alternatives. In response to this growing challenge, many countries have enacted energy policies that actively support the integration of renewable energy sources, particularly photovoltaic (PV) systems, owing to their high efficiency, environmental sustainability, and declining costs. However, integrating PV systems into the electrical grid—especially within Three-Phase networks—introduces significant technical complexities, such as power flow control, grid stability, and power quality management. Addressing these issues necessitates the implementation of advanced control strategies, including inverter control, current regulation, grid synchronization through phase-locked loops (PLL), and signal filtering techniques. This chapter presents a detailed examination of the architecture and control methodologies of a Three-Phase Grid-Connected PV system. It provides a comprehensive modeling framework for essential components such as the load, grid interface, and DC-AC inverter, along with an in-depth evaluation of control techniques including hysteresis control, current regulation, and model predictive direct current control. Furthermore, a simulation model is developed to analyze the dynamic behavior of the system and assess the effectiveness of the proposed control strategies in optimizing power injection and maintaining grid stability.

1. Grid-Connected System

The Grid-Connected PV system proposed in this study, illustrated in Figure (III.1)**,** operates by connecting the photovoltaic (PV) array in parallel with the public electrical grid**.** These systems are designed to inject the generated electrical energy directly into the utility network**,** ensuring efficient integration with existing power infrastructure.

In such configurations, the DC electrical energy produced by the PV modules is converted into AC through a DC-AC inverter, which plays a critical role in system operation. This inverter not only maximizes power extraction from the PV array but also **e**nsures compliance with grid voltage and frequency standards**,** enabling stable energy

injection into the grid or direct supply to local loads**.**

Unlike off-grid PV systems, which rely on battery storage**,** Grid-Connected systems leverage the inverter **as** the central component**,** effectively eliminating the need for energy storage. The inverter is thus the core of the system's control and energy management, ensuring seamless interaction between the PV generation unit and the electrical grid while optimizing power flow and maintaining operational stability.

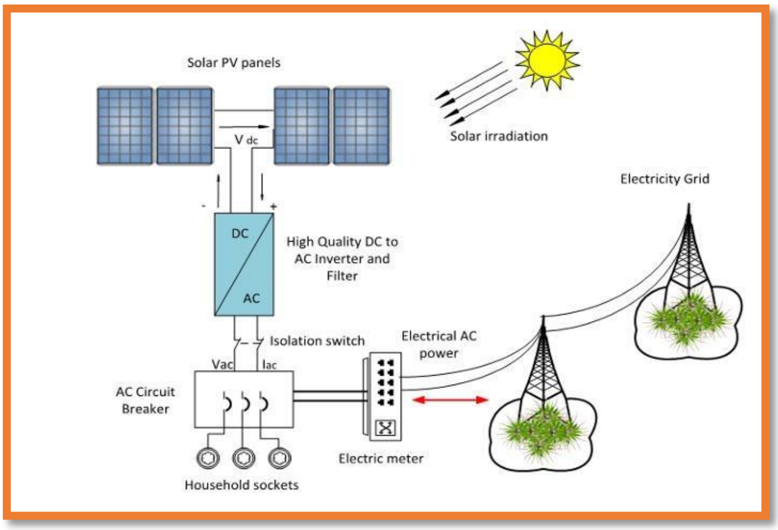


Figure (III.1): Diagram of a Grid-Connected system.

2. Control Structure of Grid-Connected Inverter

The control system of a Grid-Connected inverter plays a crucial role in regulating the injection of power into the electrical grid**,** ensuring stable and efficient energy transfer from the distributed photovoltaic generator**.** To achieve this, a cascaded control structure is typically adopted, consisting of two interconnected loops

Among the most widely used configurations is the combination of an outer power control loop and an inner current control loop. The outer loop governs the power delivery to the grid**,** optimizing energy flow, while the inner loop precisely tracks the reference current, maintaining synchronization and ensuring steady-state operation**.**

In this study, a hysteresis current control technique is implemented within the natural (a b c) reference frame**.** As illustrated in Figure (III.2)**,** this approach provides a rapid

dynamic response and high robustness**,** making it highly suitable for Grid-Connected inverter applications**,** particularly in maintaining grid stability and power quality**.**

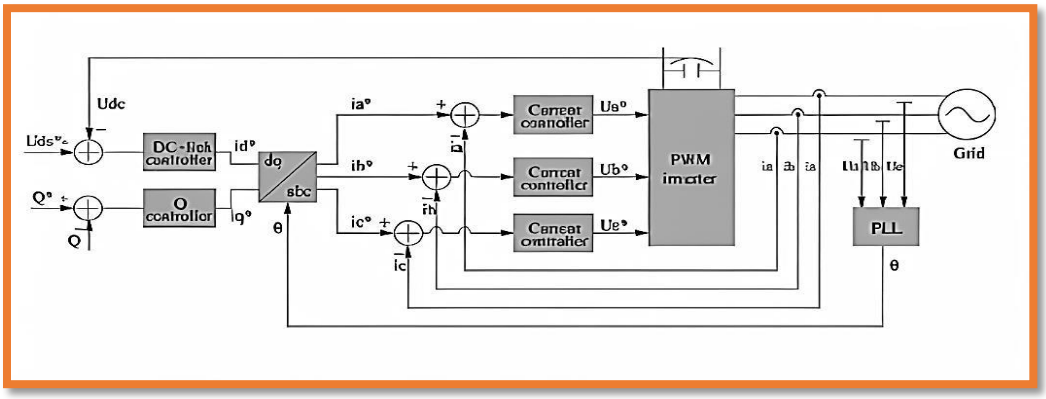


Figure (III.2): Control Structure by hysteresis current control technique.

In this study, a hysteresis current control technique is employed within the natural (abc) reference frame. As illustrated in Figure (III.2), this method offers a fast dynamic response and high robustness, making it particularly well-suited for Grid-Connected inverter applications where maintaining grid stability and power quality is essential.

Alternatively, when control is implemented in the synchronous reference frame, sinusoidal electrical variables, such as voltages and currents, are transformed into a rotating reference frame aligned with the grid frequency, effectively converting them into DC quantities. This transformation enables the use of Proportional-Integral (PI) controllers, which provide effective regulation and stability, particularly when managing DC signals in Grid-Connected systems. The general control structure in the synchronous reference frame is depicted in Figure (III.3), illustrating the interaction between controlled parameters and system response.

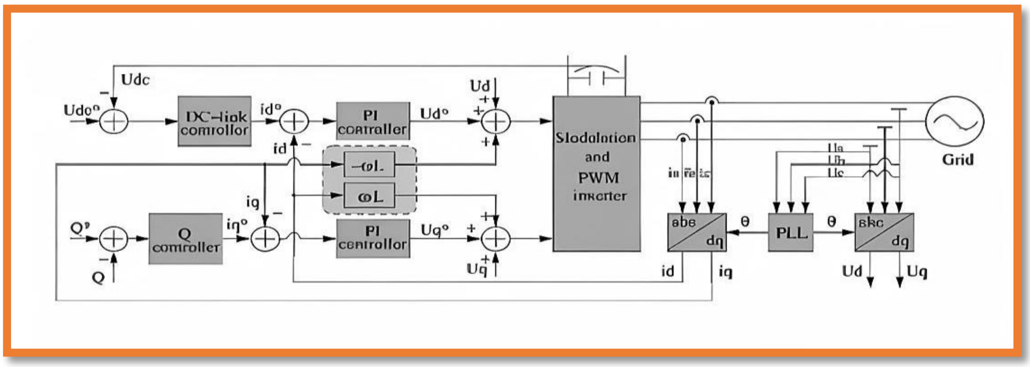


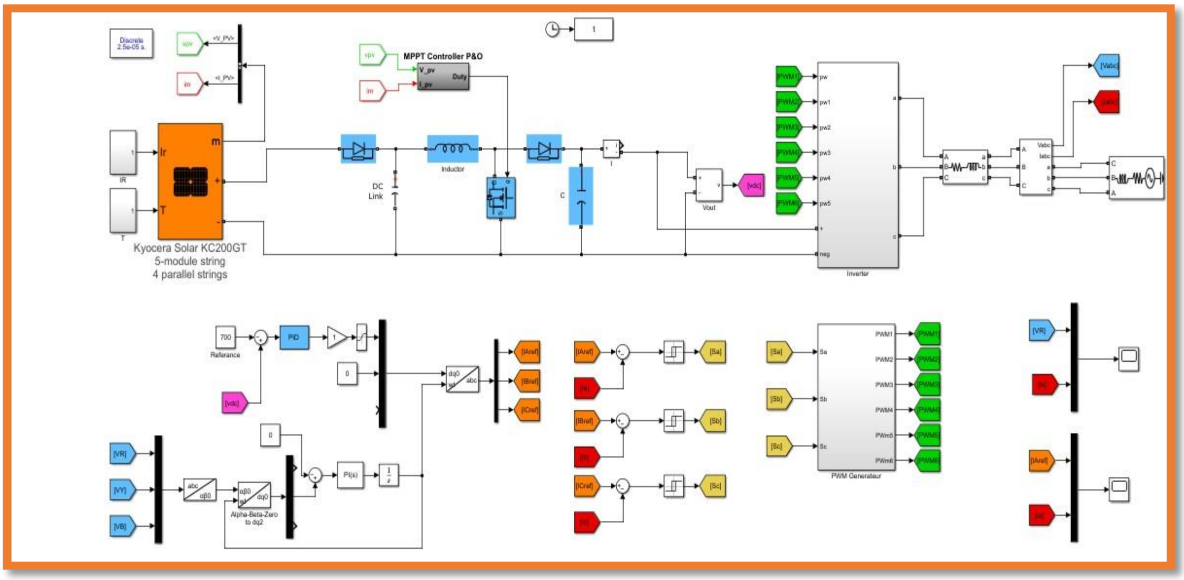
Figure (III.3): General Control Structure in synchronous reference frame

3. Proposed Grid-Connected Photovoltaic System

The proposed residential Grid-Connected photovoltaic (PV) system, illustrated in Figure (III.4), integrates all the essential components necessary for efficient solar energy conversion and seamless grid integration. These components include a PV array, a boost DC-DC converter, a Maximum Power Point Tracking (MPPT) controller, a voltage source inverter (VSI), a transformer, and the utility grid connection.

The PV array operates under fluctuating environmental conditions, primarily influenced by variations in temperature and solar irradiance. A performance evaluation is conducted in the simulation section, where temperature ranges from 25°C to 45°C, while irradiance gradually decreases from 1000 W/m² to 200 W/m². The impact of these variations on the PV array's output power is thoroughly analyzed to assess the system's adaptability and efficiency.

To optimize power extraction, the Incremental Conductance (INC) MPPT algorithm is implemented for regulating the switching of the boost converter. By continuously measuring voltage and current from the PV array, the MPPT controller dynamically adjusts the duty cycle of the converter, ensuring maximum power harvesting under diverse operating conditions. This control methodology enhances system performance, stability, and energy utilization efficiency, making the Grid-Connected PV system more reliable and adaptable to real-world scenarios.



3.1 The Load

In this study, a balanced resistive-inductive (RL) load is integrated into the AC side of the system. This type of load is widely utilized in simulation and analytical studies to effectively represent typical consumer appliances, ensuring uniform power distribution across all three phases. Maintaining balanced phase operation is fundamental for precisely evaluating the performance of the Grid-Connected photovoltaic system, as it allows for a comprehensive assessment of system stability, efficiency, and dynamic behavior under real-world operating conditions.

3.2 Modeling of the Grid interface

The electrical grid is modeled as a Three-Phase voltage source**,** characterized by a line-to-line RMS voltage of 400 V**.** This grid representation is directly connected to the photovoltaic (PV) system**,** as illustrated in Figure (III.5)**.**

This simplified model facilitates a comprehensive analysis of grid interaction, voltage synchronization, and power injection behavior under standard operating conditions**.** By establishing a clear framework for evaluating system response**,** this modeling approach enhances the accuracy of performance assessments and provides valuable insights into Grid-Connected PV system dynamics**.**

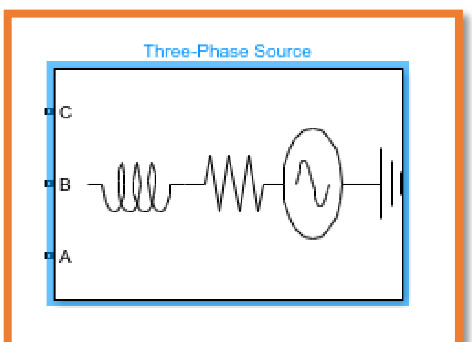


Figure (III .8): Block diagram of an RL filter -Simulink. on MATLAB

3.3DC-AC Converter

In this project, a Three-Phase, two-level inverter is utilized, as shown in Figure (III .6) MOSFETs are selected as the switching devices due to their superior switching frequency compared to IGBTs, which significantly enhances the inverter's dynamic performance by enabling faster switching and improved response time.

The DC-link capacitor serves as the primary energy storage unit, ensuring voltage stability and facilitating efficient DC-to-AC power conversion. This configuration optimizes energy transfer efficiency and is particularly well-suited for Grid-Connected photovoltaic systems, where stable voltage regulation and high-frequency operation are essential for ensuring seamless grid integration and maintaining system reliability.

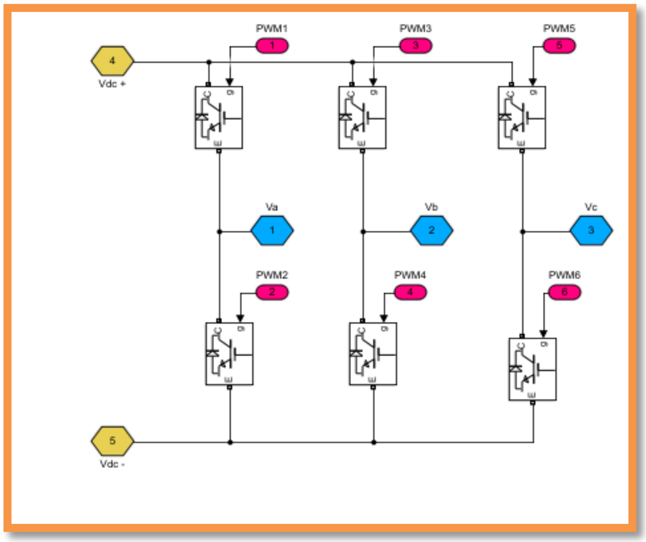


Figure (III .6): Inverter schematic.

3.4 Hysteresis Control of the Inverter

In this application, a hysteresis current control technique is implemented to regulate the inverter's output current, ensuring fast dynamic response and high accuracy in tracking the reference current waveform. This method offers robust performance, making it particularly suitable for Grid-Connected photovoltaic systems, where precise current regulation is essential for stable power injection into the grid.

Additionally, a conventional Proportional-Integral (PI) controller is employed to maintain the DC bus voltage at a constant level, effectively stabilizing the power conversion process and enhancing overall system reliability. By integrating both hysteresis current control and PI voltage regulation, the system achieves optimized energy management, ensuring efficient operation under varying load and grid conditions.

3.5 Current Control

Current control is recommended in all applications centered around a voltage inverter because it ensures, on one hand, good protection and stability.

In addition, it allows the control of the current waveform during a period of the network, which enables compensation for disturbances caused by load transients, nonlinearities, and switching delays. Indeed, control strategies are applied to achieve rapid modulation of the voltage at the input/output of the converter such as PWM techniques. Also, current control is essential in certain applications such as active rectification and filtering, where the current must be instantly controlled to impose given active and reactive powers, to minimize harmonic currents, and to improve the power factor of the system.

Hysteresis Current Control (HCC) involves maintaining the current within a band enveloping its reference. Each violation of this band gives a switching command to the switches. Figure (III .7) illustrates the principle of hysteresis current control with fixed two-level band. The difference between the reference current and the measured current is applied to the input of a hysteresis comparator, whose output provides the control command for the corresponding arm of the bridge.

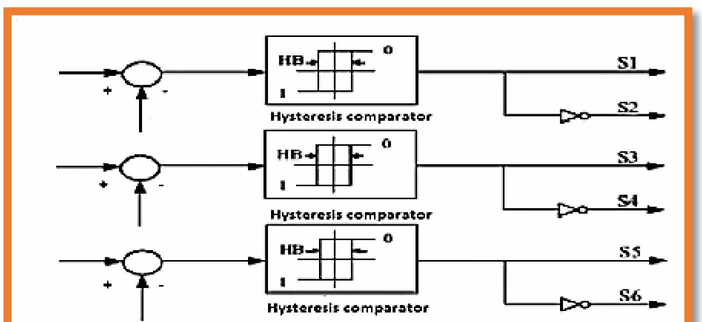


Figure (III .7): current control.

The three currents at the input of the bridge are controlled using three fixed-band hysteresis comparators. The combination of the three outputs of these comparators determines the control commands for the switches constituting the bridge. Indeed, the determination of the switching instants follows the following logic:

$$\begin{cases} \mathbf{i_i^* - i_i = \frac{\Delta I}{2} \rightarrow S_i = 0} \\ \mathbf{i_i^* - i_i = -\frac{\Delta I}{2} \rightarrow S_i = 1} \end{cases} \qquad \mathbf{i = a, b, c}$$

The role of the regulation loop of the inductor current is to maintain this current at a constant reference value. The regulation of this is achieved by adjusting the amplitude of the current references used to control the active power flow between the grid and the DC bus.

3.6 Model a phase-locked loop (PLL)

The grid phase information is obtained using a Phase-Locked Loop (PLL), which plays a critical role in achieving accurate synchronization in Grid-Connected photovoltaic systems. The Simulink model of the PLL structure, shown in Figures III.4 and III.6, enables precise estimation of the grid phase angle, ensuring seamless integration of photovoltaic-generated power into the electrical network.

This phase angle is then applied in the dq (direct-quadrature) transformation of both voltage and current signals, allowing for effective control and analysis within a rotating reference frame aligned with the grid voltage vector. By utilizing this transformation, the system achieves precise regulation of active and reactive power, thereby enhancing grid stability, improving power factor, and ensuring efficient system operation

3.7 Filter

In this design, an RL filter is employed to interface the inverter with the grid, ensuring smooth power delivery and mitigating unwanted harmonic distortions. Since the inverter operates using pulse-based gating signals, the output current often contains significant harmonic components, which can compromise power quality and affect the overall performance of the Grid-Connected photovoltaic system.

The RL filter effectively attenuates high-frequency harmonics, thereby smoothing the current waveform and enhancing the quality of power injected into the grid. By reducing harmonic distortion, the filter plays a crucial role in ensuring system stability, improving grid compliance, and maintaining efficient energy conversion within the photovoltaic system

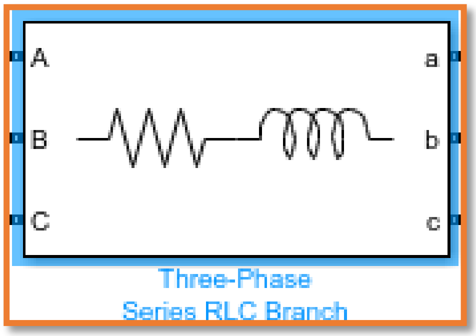


Figure (III .8): Block diagram of an RL filter

4. Predictive Direct Current Control of the Two-Level Inverter

The schematic diagram of a Three-Phase Grid-Connected inverter, employing a predictive current control strategy, is illustrated in Figure III.7. This approach utilizes a cost function to minimize the error between the reference and predicted currents within the synchronous reference frame, ensuring fast and precise current tracking while optimizing system performance.

In this control scheme, the d-axis of the synchronous frame is aligned with the grid voltage vector, representing the active current component, whereas the q-axis, corresponding to reactive current, is set to zero to achieve unity power factor operation. The grid voltage phase angle is extracted using a Phase-Locked Loop (PLL) block, which also plays a crucial role in regulating the DC-link voltage, thereby ensuring proper synchronization and voltage stability.

Utilizing Kirchhoff's laws, the dynamic behavior of the Three-Phase Grid-Connected inverter can

be mathematically formulated in the abc reference frame using the following state-space model

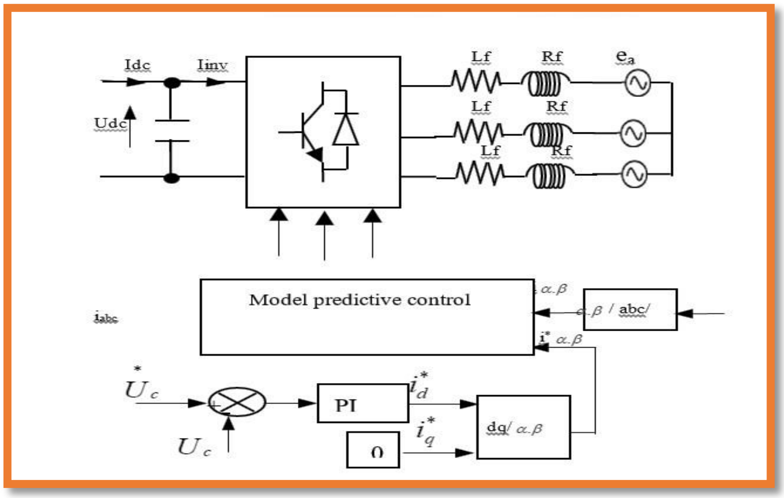


Figure (III. 9): Two -level inverter with grid connection.

The seven values of voltage vector U (k) generated by the inverter expression as

$$U_{abc} = \frac{1}{3} Vdc\, T_{abc} S_{abc}$$

T_{abc} is the transformation matrix, which can be written as

$$T_{abc} = \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}$$

The grid side voltages are given by

$$V_{abc} = U_{abc} + Lf \frac{d}{dt} i_{abc} + Rf i_{abc}$$

The grid side voltages $V\alpha, V\beta$ written as follow

$$V_{\alpha\beta} = U_{\alpha\beta} + Lf\frac{d}{dt}i_{\alpha\beta} + Rfi_{\alpha\beta}$$

The voltages in rotating reference frame (d-q) components can be expressed as

$$V_d = U_d + Lf\frac{d}{dt}i_d + Rfi_d - \omega\, Lf\, i_q$$

$$V_q = U_q + Lf\frac{d}{dt}i_q + Rfi_q - \omega\, Lf\, i_d$$

The active and reactive power are obtained as

$$P = \frac{3}{2}(V\alpha\; i\alpha + V\beta\; i\beta)$$

$$Q = \frac{3}{2}(V\beta\; i\alpha - V\alpha\; i\beta)$$

The predictive current at the discrete-time model gives by

$$i_{\alpha\beta}(k+1) = \left(1 - \frac{Rf\; T_s}{Lf}\right)i_{\alpha\beta}(k) + \frac{T_s}{Lf}\left(V_{\alpha\beta}(k) - U_{\alpha\beta}(k)\right)$$

The best voltage vector applied to the DC/AC inverter based on the cost function described as

$$gc = \left|i_\alpha(k+1) - i_{\alpha\, ref}(k+1)\right| + \left|i_\beta(k+1) - i_{\beta\, ref}(k+1)\right|$$

When $i_\alpha\,(k+1)\; i_{\beta\, re}\,(k+1)$ are the references value of the grid current at t = k + 1.

5. Simulation of the PV Grid-Connected Inverter

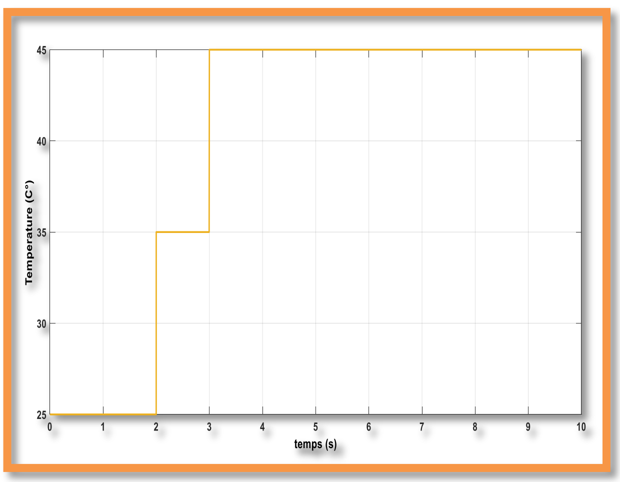
The system model was simulated in the MATLAB/Simulink environment to evaluate the performance of the proposed control scheme under varying operating conditions. The system behavior was analyzed at different irradiance levels, where solar insolation gradually decreased from 1000 W/m² to 800 W/m², while temperature increased from 25°C to 45°C.

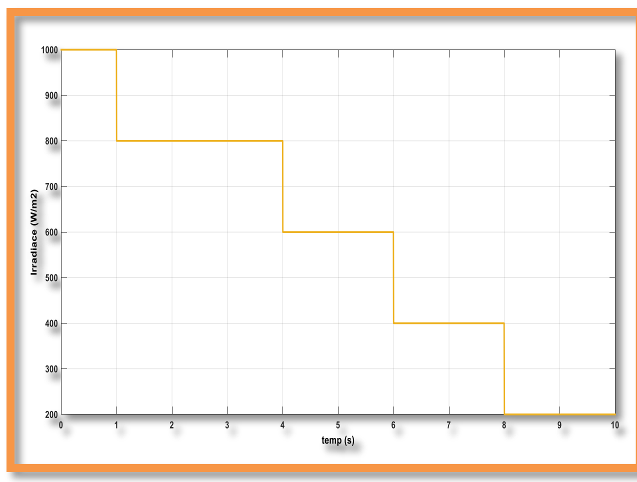
To ensure unity power factor operation, the reactive current was maintained at zero throughout the

simulation. The active and reactive voltage signals generated by the current controller were transformed into three modulating signals, serving as references for the MPPT PWM generator, which produced the desired output voltage.

Figure III.14 illustrates the PV panel output voltage, highlighting that despite fluctuations in temperature and irradiation, the PV panel consistently operates at its Maximum Power Point (MPP) voltage. Additionally, the shoot-through duty ratio is dynamically adjusted to maintain a constant peak PV current, reinforcing the stability of the control strategy.

Figures III.12 and III.13 depict the system output power and grid current, respectively. A comparative analysis between the simulated PV voltage and output power and the power





characteristics discussed in Section 2 demonstrates a strong correlation, validating the effectiveness of the proposed MPPT method in achieving optimal energy conversion and stable grid integration.

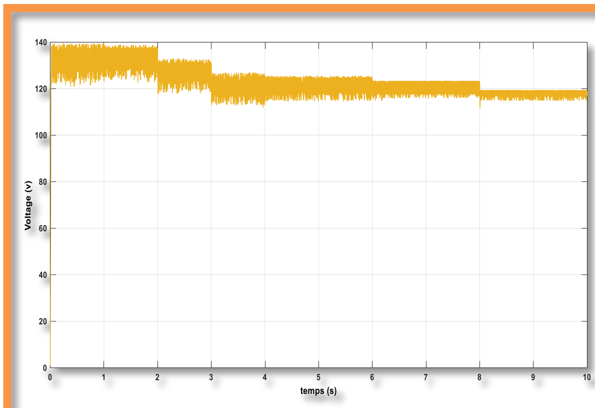


Figure (III .12): "Waveform of output voltage of PV"

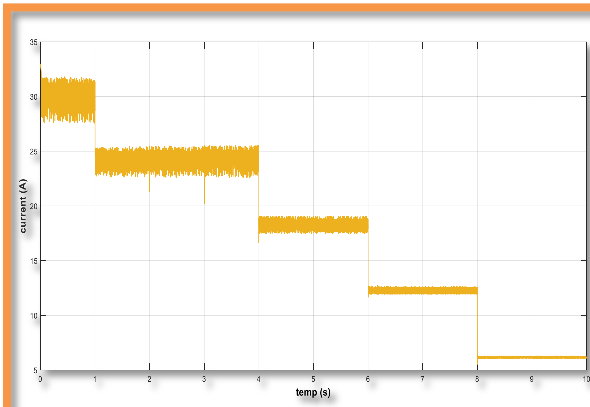


Figure (III .13): "Waveform of output current of PV**"**

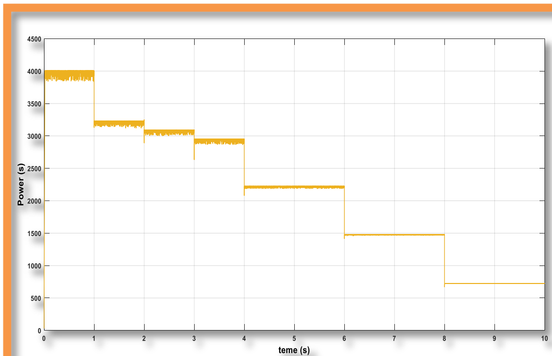


Figure (III .14): "Waveform of output power of PV"

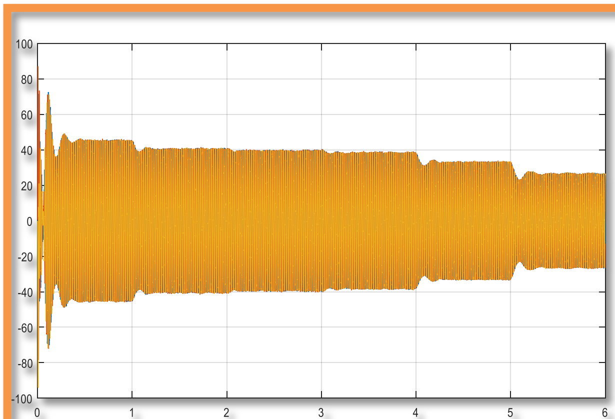


Figure (III .15): inverter output currents in abc frame

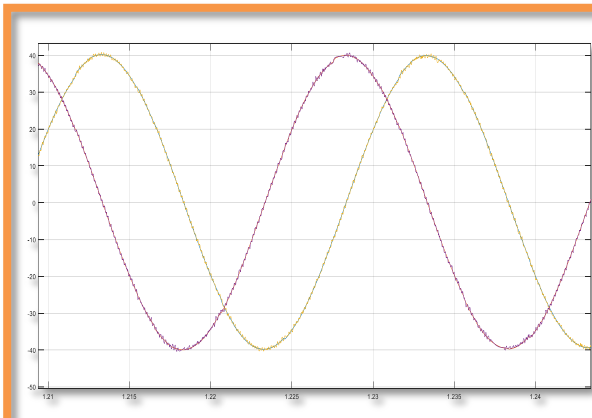


Figure (III .16): Zoom of reference and inverter output currents in the $\alpha - \beta$ frame

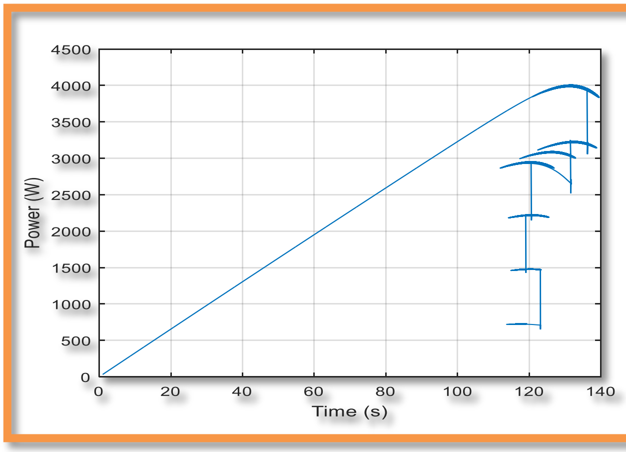


Figure (III .17): MPPT tracking

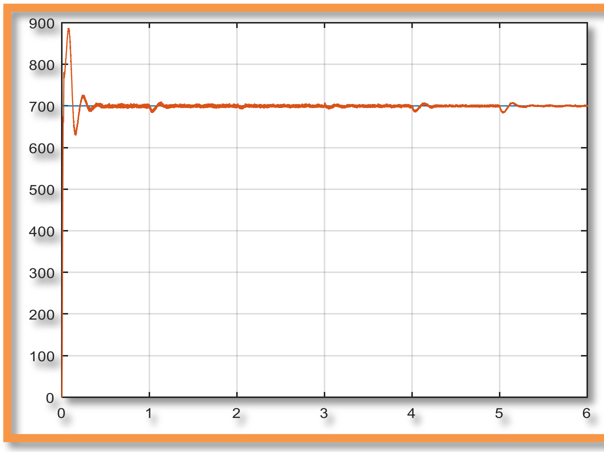


Figure (III .15): "waveforms of the alternating currents injected to the grid"

The detail performance of MPPT under diverse temperature and illumination change, it can be noted that the output power of the PV array, according to Figure (III .12) indicates proximity of the point of maximum power.

As see in Figure (III .15) the reference currents change dynamically, the model predictive current control has the ability of fast current regulation and guarantee the output currents to meet the grid requirements.

Furthermore, the currents $\alpha-\beta$ track their references with a very good performance in the steady state and in the transient in Figure (III .16)

The digital simulation results driven grid connected photovoltaic (PV) inverters, ensure good dynamic speed trajectory tracking and near maximum power point. as illustrated in Figure (III .17)

Conclusion

This study successfully developed and analyzed a MATLAB/Simulink-based predictive current control model for a Grid-Connected solar PV system. The proposed control strategy ensures that when power balance is maintained at the DC-link, the inverter output current precisely tracks the reference current generated by the DC-side controller, enabling efficient and accurate power transfer to the utility grid.

Moreover, the control system exhibited fast and reliable regulation of the DC-link voltage, ensuring stable operation under dynamic and fluctuating power conditions. The simulation results validate that the predictive current control approach delivers rapid dynamic response, robust current tracking, and improved overall efficiency, reinforcing its effectiveness and suitability for Grid-Connected photovoltaic applications.

GENERAL CONCLUSION

General Conclusion

This research focuses on the control of Three-Phase Grid-Connected photovoltaic (PV) systems, an area of growing significance due to the increasing demand for renewable energy and efficient electricity integration. To ensure a comprehensive analysis, the study was divided into three interconnected chapters.

In Chapter I, the fundamental concepts of photovoltaic systems were introduced, covering solar radiation characteristics, types of PV cells, and operational principles. The modeling of PV cells was also discussed, along with the effects of environmental conditions such as irradiation and temperature on system performance.

Chapter II explored Maximum Power Point Tracking (MPPT) in photovoltaic systems, examining different MPPT methods, with a particular focus on the Perturb and Observe (P&O) algorithm. The role of DC-DC converters, particularly the Boost Converter, was analyzed to understand how power conversion improves energy efficiency and system performance.

Chapter III delved into the control strategies for Grid-Connected PV systems, emphasizing the structure and management of energy injection into the grid. Key topics included grid interface modeling, current control techniques, phase-locked loop (PLL) synchronization, and filtering methods to maintain power quality. Additionally, predictive direct current control was introduced as an advanced technique for optimizing system efficiency.

The final phase of this research involved simulating and evaluating the performance of the Grid-Connected PV system using PSIM software. Each subsystem was individually tested before conducting a full-system analysis to assess the overall effectiveness of energy injection. The results confirmed that the proposed system successfully extracts and delivers maximum available power to the grid, demonstrating its feasibility and operational efficiency.

This study contributes to the optimization of Grid-Connected PV systems by offering insights into modeling, control mechanisms, and performance evaluation. Future research could focus on developing more advanced MPPT algorithms, enhanced predictive control techniques, and system integration improvements to further refine efficiency and reliability in practical applications.